Hybrid tuning of a robotic manipulator controller with a database

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Abstract. In this paper a method of adaptation with hybrid tuning of a robotic manipulator control system with PD controller is considered. The adaptations of the controller parameters and compensating signal are carried out online and independent using modified simplex search algorithms. To increase the performance of the adaptive control system, the values obtained during adaptation process are stored in a database. The database stores these values and the system state, at which they were obtained during the training phase, and in the control phase the database returns the values according to the current state of the system. Efficiency of the proposed methods is verified by simulations. The results show advantage of the adaptive control system with the database.

1. Introduction

There are several approaches to tuning controller parameters based on data from a control system. The simplest approach is iterative feedback tuning (IFT) method, proposed in [1]. It minimizes the cost function by updating parameters of the controller. The goal of optimization is explicitly represented, that is achieving the desired tracking result. The main drawback of this method is that the experiment on the control system must be conducted each iteration. There are alternative approaches, virtual reference feedback tuning (VRFT) presented in [2] and fictitious reference iterative tuning (FRIT) presented in [3]. They were designed to tune the controller parameters so it provides the desired control system performance using tuning procedure, that utilizes the data from one-shot experiment on the control system, provided that reference model of the control system and inverse characteristics of the controller are known.

The most common controller for tuning is PID controller, due to its simplicity and widespread use in real control systems [4]. Tuning parameters of PID controller based on the fictitious reference input attracts attention of researchers as an efficient method to achieve the required control performance with a minimum number of experiments on the control system [5-9]. FRIT was created as an offline parameter tuning method. Modification was proposed to make FRIT an online parameter tuning method [10] suitable to work in a system with a non-stationary object.

In this paper an adaptive controller with hybrid tuning and a database is presented. A Modified simplex search is used to tune controller parameter and compensating signal independently. It uses FRIT approach to the get cost function without carrying out additional experiments on the system. The results of the adaptation are stored in the database during the memorizing phase. Then in the control phase the database returns its content according to the current system state.
2. Problem statement

A manipulator with \( n \) links is described by a nonlinear system of differential equations (1)

\[
\mathbf{M}(\mathbf{q}(t)) \cdot \dot{\mathbf{q}}(t) + \mathbf{V}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) + \mathbf{G}(\mathbf{q}(t)) + \mathbf{F}(\mathbf{q}(t)) = \tau(t),
\]

where \( \tau(t) \) is the \( n \times 1 \) vector of torques exerting on joints (Nm); \( \mathbf{q}(t) \) is the \( n \times 1 \) vector of joint angular position (rad); \( \mathbf{M}(\mathbf{q}(t)) \) denotes the \( n \times n \) inertia matrix, \( \mathbf{V}(\mathbf{q}(t), \dot{\mathbf{q}}(t)) \) is the \( n \times n \) matrix of Coriolis and centrifugal forces; \( \mathbf{G}(\mathbf{q}(t)) \) is the \( n \times 1 \) vector of gravitational forces; \( \mathbf{F}(\mathbf{q}(t)) \) is the \( n \times 1 \) vector of joints frictional forces. Since matrices \( \mathbf{M}, \mathbf{V} \) and vectors \( \mathbf{G}, \mathbf{F} \) are tend to change the values of their elements during the manipulator movement and the identification procedures are rather complicated, a PD controller with adaptation can be used. Adaptation of the PD controller can be done by tuning either its parameters or compensating control signal or both. In this paper the control system with adaptive controller that performs hybrid online tuning [11] of the controller parameters and compensating control signal is considered. Denote the vector of controller’s tunable variables as \( \mathbf{\theta} = [\mathbf{\rho} \; \mathbf{v}] \), where \( \mathbf{\rho} \) is the vector of controller parameters and \( \mathbf{v} \) is the compensating control signal.

The control system consists of a continuous object and a discrete adaptive controller with control time \( t_{k} = k \cdot T_{0} \), where \( k \) is the discrete control time, \( T_{0} \) is the control time quantization interval.

Adaptation is carried out through each \( N_{ad} \) control steps, so the adaptation time is equal to \( t_{\kappa} = \kappa \cdot T_{0} \). We denote the discrete adaptation time as \( \kappa \) and \( T_{a} = T_{0} \cdot N_{ad} \) as the adaptation interval. Structural diagram of the proposed adaptive control system is showed in figure 1.

![Figure 1. Structural diagram of the proposed adaptive control system.](image)

3. Hybrid tuner

The controller parameters are tuned with simplex search that minimizes the cost function based on measured error. The compensating control signal is tuned using modified simplex search with FRS approach to calculate cost function. The modified simplex search cost function is a performance index of the vector of tunable variables. It’s calculated from the fictitious reference signal (FRS) [3].

Despite that controller parameters are tuned independently, they are required to calculate FRS. Denote the vector of tunable variables of compensating control tuning as \( \hat{\mathbf{\theta}}^{0}_{\kappa} = [\mathbf{p}_{\kappa} \; \mathbf{v}_{i}] \), where \( \mathbf{p}_{\kappa} \) is the vector of parameters obtained at \( \kappa \)-th step, \( i \) is an index of a simplex vertex. The FRS allows evaluating impact of the alternative sets of the controller’s tunable variables on the performance of the control system without using them in the control system. The FRS from an \( i \)-th set of controller tunable variables \( \hat{\mathbf{\theta}}^{0}_{i} \) is a reference signal that would provide a control signal equal to \( \tau(\kappa | \mathbf{\theta}_{\kappa-1}) \) if fed into a closed-loop system with the object output value \( q(\kappa | \mathbf{\theta}_{\kappa-1}) \) and the controller with the tunable
variables $\hat{\theta}^{(i)}$. The value of the FRS from the set of variables at which $q(\kappa | \theta_{k-1})$ and $\tau(\kappa | \theta_{k-1})$ are obtained is equal to the actual value of the reference signal: $r(\kappa) = \hat{r}(\kappa, \theta_{k-1})$. Define the performance index of the $i$-th set of tunable variables as

$$
\hat{Q}(\kappa | \hat{\theta}^{(i)}) = \left( \hat{q}(\kappa | \hat{\theta}^{(i)}) - q(\kappa | \theta_{k-1}) \right)^2 \rightarrow \min \quad (2)
$$

$$
\hat{q}(\kappa | \hat{\theta}^{(i)}) = P_d \hat{r}(\kappa, \hat{\theta}^{(i)}), \quad (3)
$$

where $\Theta = \{ \hat{\theta}^{(1)} : \hat{\theta}^{(i)} \in \mathbb{R}^*, \theta^- \leq \hat{\theta}^{(i)} \leq \theta^+ \}$; $\theta^-, \theta^+$ – are the vectors of minimal and maximum limits of the tunable variables; $\theta_{k-1}$ – is the current vector of the tunable variables; $\hat{r}(\kappa, \hat{\theta}^{(i)})$ – is the fictitious reference signal; $P_d$ – is the transfer function of the desired reference model. In [3] it was proved that when the sum of (2) over control steps tends to zero the sum of squared errors of the control also tends to zero.

In a control system that includes a controller $D(\theta_{k-1})$, with the current set of variables $\theta_{k-1}$, and a manipulator link as a control object, the FRS $\hat{r}(\kappa, \hat{\theta}^{(i)})$ for the considered vector of variables is calculated by the formula

$$
\hat{r}(\kappa, \hat{\theta}^{(i)}) = \hat{e}(\kappa, \hat{\theta}^{(i)}) + q(\kappa | \theta_{k-1}), \quad (4)
$$

$$
\hat{e}(\kappa, \hat{\theta}^{(i)}) = D^{-1}(\hat{\theta}^{(i)}) \tau(\kappa | \theta_{k-1}), \quad (5)
$$

where $\tau(\kappa | \theta_{k-1})$ and $q(\kappa | \theta_{k-1})$ are the input and output of the control object in the system under control of $D(\theta_{k-1})$; $D(\hat{\theta}^{(i)})^{-1}$ is the inverse regulator with the considered set of variables.

To calculate $\hat{Q}(\kappa | \hat{\theta}^{(i)})$ the input and output data of the control system from the one-shot experiment with the current set of controller variables $\theta_{k-1}$ are acquired. Define the experiment as time interval between the $\kappa-1$-th and the $\kappa$-th adaptation steps. The reference model $P_d$ is chosen such as its transient response reach steady-state value during the experiment. The simplex search at the $\kappa$-th adaptation step calculates the value of the cost function for each vertex: $\hat{Q}(\kappa | \hat{\theta}^{(i)})$; where $s$ is a number of simplex vertices. To do this, at the moment $t_e$, using $q(\kappa | \theta_{k-1})$ and $\tau(\kappa | \theta_{k-1})$ calculate FRS $\hat{r}(\kappa, \hat{\theta}^{(i)})$ for all vertices of the simplex. The presented search algorithm differs from the standard simplex search only in updating the values of the cost function at all vertices of the simplex at each adaptation step. From $q(\kappa-1 | \theta_{k-2})$, the reference transient response $\hat{q}(\kappa | \hat{\theta}^{(i)})$ for each $\hat{r}(\hat{\theta}^{(i)})$ (figure 2) and the performance index (2) are calculated.

The differences in values of $\hat{Q}(\kappa | \hat{\theta}^{(i)})$ for $i = 1, \ldots, s$ at the $\kappa$-th step of the search are determined solely by the values of $\hat{\theta}^{(i)}$, therefore we assume that the function $\hat{Q}(\kappa | \hat{\theta}^{(i)})$ is static at the $\kappa$-th step, which allows us to perform calculations at all vertices of the simplex. On the $\kappa+1$-th step, with new experimental data, the surface of the function $\hat{Q}(\kappa + 1 | \hat{\theta}^{(i)})$ can shift relatively to $\hat{Q}(\kappa | \hat{\theta}^{(i)})$, which can significantly offset the optimum and the gradient of the cost function. Therefore, updating the values of the objective function at all vertices is a necessity. To avoid large fluctuations in the variable values, only one search step is performed between the adaptation steps.
Figure 2. Experimental result and reference transient responses.

4. Storing tuning results
Since rapid changes can occur in the dynamics of the manipulator, the adaptation speed may be insufficient. If the system has successfully adapted in certain system states, then obtained results of this adaptation can be reused in these states. In this paper the results of the previous adaptations are stored in the database. During control the tunable variables are returned from the database in accordance with the current system state to be used in the controller.

The database is represented by a two-dimensional table, the cells of which contain the vectors of controller’s tunable variables. The current state is described by a point in the phase space coordinates $p = [e \ \dot{e}]$. The table is linked to the constrained area of the phase space coordinates $\Phi = \{e, \dot{e}\}$ with dimensions $w_e$ and $w_{\dot{e}}$, and broken up into regular areas. Each area $v(I_j)$ is characterized by a pair of indices $I_j = [i^{(1)} \ i^{(2)}]$, corresponding to the row and column indices of the associated table cell, the coordinates of the center of the area $v_v(I_j)$, and the size of the area $v_v, v_{\dot{e}}$ (figure 3).

Figure 3. Areas of the phase space coordinates plane.

To reduce the effect of the difference in tunable variables in neighboring cells, a weighted sum of the tunable variables from the current cell and several nearest ones is returned from the table. The final values of the tunable variables obtained from the table are calculated with
\[ \mathbf{\theta} = \sum_{j=1}^{m} \omega_j \cdot \mathbf{\theta}_j, \]  

(6)

where \( \sum_{j=1}^{m} \omega_j = 1; \ \mathbf{\theta}_j = [\mathbf{p}_j \ \mathbf{v}_j] \) is the vector of tunable variables stored in the \( j \)-th cell; \( m \) – the number of nearest considered cells; \( \omega_j \) – weight of the \( j \)-th cell. The weights are based on the distances from the coordinates of the current phase space point to the coordinates of the centers of the nearest considered areas

\[ \omega_j = \frac{1/d_j}{\sum_{i=1}^{m} 1/d_i}, \]  

(7)

\[ d_j = \|\mathbf{p} - \mathbf{v}_j(\mathbf{1}_j)\|. \]  

(8)

The values of the tunable variables in the cells are updated according to the following law

\[ \mathbf{\theta}_j = \omega_j \cdot \mathbf{\theta}_\kappa + (1 - \omega_j) \cdot \mathbf{\theta}_j, \]  

(9)

where \( \mathbf{\theta}_j, \mathbf{\theta}_\kappa \) are the new and old vectors of \( j \)-th cell respectively, \( j = 1, \ldots, m \); \( \mathbf{\theta}_\kappa \) is the vector of tunable variables returned from hybrid tuner at the \( \kappa \)-th adaptation step.

The database works in two modes: storage and control. In the storage mode, the database is continuously updated by hybrid adapter. By using the optimization algorithms, the hybrid adapter obtains new variable values that are used for control and for updating the database according to equation (9). This mode is used for initial configuration of the database. In the control mode, the adapter gets the values of the tunable variables from the database with equation (6).

5. Experiments

The experiments were conducted on the model of the robotic manipulator PUMA P560. The second joint was considered as control object, since it is the most influenced by the moments of inertia and the gravity moments from the subsequent links. We denote the adaptive PD controller with hybrid tuner and the database in the storage mode as PD+SM, this mode corresponds to the adaptive controller without the database. We also denote the same adaptive controller with the database in the control mode as PD+CM. The resulting trajectories are shown in figure 4.

![Figure 4](image-url)  

Figure 4. Results of modeling with different step sizes.
The properties of the transient responses of the system with considered controllers are presented in table 1.

| Criterion                  | Reference          | $r(t_s) = 20$ (grad) | $r(t_s) = 45$ (grad) | $r(t_s) = 60$ (grad) |
|----------------------------|--------------------|----------------------|----------------------|----------------------|
|                            | PD+SM              | 14.7                 | 14.4                 | 16.2                 |
|                            | PD+CM              | 7.4                  | 4.7                  | 2.0                  |
| Overshoot (%)              |                    |                      |                      |                      |
| Settling time (sec)        | PD+SM              | 2.35                 | 3.02                 | 1.98                 |
|                            | PD+CM              | 0.59                 | 0.44                 | 0.4                  |
| Steady-state error (grad)  | PD+SM              | -0.06                | 0.01                 | -0.03                |
|                            | PD+CM              | 0.03                 | 0.04                 | 0.01                 |
| Rise Time (sec)            | PD+SM              | 0.89                 | 1.04                 | 0.66                 |
|                            | PD+CM              | 0.28                 | 0.65                 | 0.44                 |

6. Conclusion

In this paper the adaptive control with the database is presented. The hybrid tuner successfully determines values of the controller variables that make the object output follow the reference input. According to the results of the experiments, the use of the database leads to significant improvements in the properties of the transient response, especially overshoot and regulation time. The studies showed: increase in productivity of the adaptive control system when using the database to memorize the results of adaptation; the suitability of using the database for manipulator control tasks.

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