AN OPTIMAL PID TUNING METHOD FOR A SINGLE-LINK
MANIPULATOR BASED ON THE CONTROL
PARAMETRIZATION TECHNIQUE

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Abstract. A control parametrization based optimal PID tuning scheme for
a single-link manipulator is developed in this paper. The performance speci-
fications of the control system are formulated as continuous state inequality
constraints. Then, the PID optimal tuning problem of the single-link manipu-
lator can be formulated as an optimal parameter selection problem subject to
continuous inequality constraints. These continuous inequality constraints are
handled by the constraint transcription method together with a local smoothing
technique. In such a way, the transformed problem becomes an optimal
parameter selection problem in a canonical form, which can be solved efficiently
by control parametrization method. Since approach is using the gradient-based
method, the corresponding gradient formulas for the cost function and the con-
straints are derived, respectively. The effectiveness of the proposed method is
demonstrated by numerical simulations.

1. Introduction.

1.1. Background and motivation. Reliable and efficient manipulators play an
important role in the modern industry such as production line, safety and explosion-
proof. The fundamental job for manipulator control system is to control the ma-
nipulators to follow certain reference input under certain performance specifica-
tions. Most of the manipulators are highly nonlinear multi-input and multi-output
(MIMO) systems. In addition, disturbance, imperfect dynamic modeling and pa-
rameter perturbations are usually associated, which make the control system design
of the manipulators more difficult. Popular control strategies for the manipula-
tors are PID control, adaptive control, robust control, neural network control and
fuzzy control, and iterative learning control [15]. However, PID control algorithm is

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still the most used control strategy which is adopted for more than 90\% of control systems in practice [34]. For the PID control, the key problem is to determine the corresponding proportional, the integral and the derivative parameters, respectively, and this motives the study of this paper.

1.2. Literature review. There are many PID parameter tuning methods in the literature, which can be classified into two streams: conventional tuning method and intelligent tuning method. Conventional PID tuning method was proposed by Ziegler-Nichols in [45]. Now there are many improved versions by considering the system characteristics [1],[27],[29] or the relay feedback [35],[43]. Intelligent tuning method [2] and [3] was proposed by Astrom in 1988, which consists of the model-based one and rule-based one. The former is based on the Z-N method, and it adjusts the parameters by identifying the input and output [4], [5]. The latter does not require the exact system model information [44], [6], [28]. Based on the rules similar to manual setting by experienced operators, it tunes the setting parameters according to the transient response, set value change, load and disturbance change [11], [7].

1.3. Contributions. A control parameterization based optimal PID tuning method is developed for a single-link manipulator without simplification and linearization of the dynamic system in this paper. To meet the control system design requirements, the performance specifications such as rise time, overshoot and settling time are modeled into continuous state inequality constraints [17]. The optimal PID tuning problem of a single-link manipulator is transformed into an optimal parameter selection problem subject to continuous state inequality constraints, which is, in fact, a semi-infinite programming problem [14]. The constrained transcription method [31, 39, 40, 41, 42, 12, 16] and the exact penalty function method [13, 14, 30, 33, 8, 38] are the effective methods to solve such problems [18, 19]. In this paper, constraint contraint transcription method together with a local smoothing technique is adopted. By doing so, the original problem is converted into an optimal control problem in a canonical form [31], which can be solved by the control parameterization method [37, 20, 21, 22, 23, 26, 24, 10]. Since it is a gradient based method, the gradient formulas for the cost function and the constraints are derived [25], respectively. The numerical simulations of a position tracking problem show that the proposed method can effectively achieve the required performance.

1.4. Organization. The rest of this paper is organized as follows. In Section 2, the model of the rigid single-link manipulator is provided and the optimal PID tuning problem is formulated. In Section 3, the continuous state inequality constraints are transformed into canonical constraints with the constraint transcription method. The corresponding gradient formulas for the cost function and constraints are derived, respectively, in Section 4. In Section 5, some numerical results are given to demonstrate the effectiveness of the proposed method. Then, we conclude our paper with some remarks in Section 6.

2. Problem statement. The dynamic equation of a single-link serial nonredundant robot manipulator, is given as follows [15]:

\[
\ddot{q}(t) = \frac{2}{I} \dot{q}(t) - \frac{1}{I} mgl \cos(q(t)) + \frac{1}{I} \tau(t)
\] (1)
where $I = \frac{4}{3}ml^2$, $m$ is the mass of the manipulator, $g$ is the acceleration of gravity, $l$ is the length of the manipulator, $q$ is manipulator angle, and $\tau$ is the torque input.

By setting $x_1(t) = q(t), x_2(t) = \dot{q}(t), u(t) = \tau(t)$, the dynamic equation (1) can be rewritten into the form of the state-space model as

$$
\begin{cases}
\dot{x}_1(t) = x_2(t) \\
\dot{x}_2(t) = \frac{1}{l}u(t) - \frac{2}{l}x_2(t) - \frac{3g\cos(x_1(t))}{4l}
\end{cases}
$$

with the initial condition

$$x(0) = [0 \ 0]^T \tag{3}$$

Here, we set terminal time $T = 2s$.

The PID controller is adopted which can be written as

$$u(t) = k_pe(t) + k_I \int_0^t e(s)ds + k_D \dot{e}(t) \tag{4}$$

where $e(t) = q(t) - q_d$ is the position error, $q_d \in \mathbb{R}$ denotes the desired constant joint position, $k_P$, and $k_I$ and $k_D$ are the proportional, integral and derivative gains of the PID controller, respectively. Our goal is to determine the PID control gain $k = [k_P \ k_I \ k_D]^T$ in an optimal sense.

Now we consider the classic performance specifications of the control system. In practice, a large overshoot is undesirable. To avoid it, the following constraint is imposed on the manipulator angle $x_1(t)$, which can be written as

$$g_1(t) = x_1(t) - 1.05q_d \leq 0, \quad t \in [0, 2s] \tag{5}$$

For the rise time and the setting time requirements, the manipulator angle is required to reach at least 90% of the desired reference input in 0.1s and reach at least 98% of the desired reference input in 0.2s. Thus, we have the constraint

$$g_2(t) = h(t) - x_1(t) \leq 0, \quad t \in [0, 2s] \tag{6}$$

where

$$h(t) = \begin{cases}
0, & t \in [0, 0.0275), \\
8t - 0.22, & t \in [0.0275, 0.14], \\
1.33t + 0.7138, & t \in (0.14, 0.2], \\
0.98, & t \in (0.2, 2] 
\end{cases} \tag{7}$$

We illustrate the performance specifications $g_1(t)$ and $g_2(t)$ in Figure 1.

To cater for the saturation property of the actuator, we impose upper and lower bounds on $u(t)$, which can be written as

$$g_3(t) = u(t) - 150 \leq 0, \quad t \in [0, 2s] \tag{8}$$

$$g_4(t) = -u(t) - 150 \leq 0, \quad t \in [0, 2s] \tag{9}$$

(5)-(6) are continuous state inequality constraints. However, (8) and (9) are not in this form due to the integral item in (4). For this, we introduce a new state variable

$$x_3(t) = \int_0^t e(s)ds \tag{10}$$

By substituting (10) back into (4), the PID controller becomes

$$u(t) = k_P(x_1(t) - q_d) + k_Ix_3(t) + k_Dx_2(t) \tag{11}$$
By replacing (8) and (9) with $u(t)$ in (11), we have

\[ g_3(t) = k_P(x_1(t) - q_d) + k_I x_3(t) + k_D x_2(t) - 150 \leq 0, \quad t \in [0, 2s] \] (12)

\[ g_4(t) = -k_P(x_1(t) - q_d) - k_I x_3(t) - k_D x_2(t) - 150 \leq 0, \quad t \in [0, 2s] \] (13)

Obviously, (12) and (13) are continuous state inequality constraints.

By considering (10), the new state-space model becomes

\[
\begin{aligned}
\dot{x}_1(t) &= x_2(t) \\
\dot{x}_2(t) &= \frac{1}{I} u(t) - \frac{2}{I} x_2(t) - \frac{3g \cos(x_1(t))}{4l} \\
\dot{x}_3(t) &= x_1(t) - q_d
\end{aligned}
\] (14)

and the initial condition is

\[ x(0) = [0 \ 0 \ 0]^T \] (15)

For tracking the reference signal, the cost function is chosen as

\[ J(k) = \int_0^2 [x_1(t) - q_d]^2 dt \] (16)

Now we formally state the optimal PID parameters tuning problem as:

**Problem P.** Given the system (14), find a PID control gain $k$ such that the cost function (16) is minimized subject to the continuous state inequality constraints (5), (6), (12) and (13).

Obviously, Problem P is an optimal parameter selection problem subject to continuous state inequality constraints.
3. **Problem transformation.** The continuous state inequality constraints (5), (6), (12) and (13) are difficult to be satisfied, because each constraint has an infinite number of constraints. In this section, we shall use the constraint transcription method together with a local smoothing technique [36], [31], [39], [40], [9], [32] and [38] to transform (5), (6) and (12) into the canonical form. Towards this goal, we consider the following equality constraint

\[
\int_{0}^{2} \max \{g_{i}(t),0\} \, dt = 0, \quad i = 1, 2, 3, 4 \tag{17}
\]

It is easily to verify equivalence between (17) and (5), (6) and (12).

Since (17) is non-differentiable, we approximate (17) by a smooth function

\[
L_{i, \varepsilon}(g_{i}(t)) = \begin{cases} 
0, & g_{i} < \varepsilon, \\
(g_{i}(t) + \varepsilon)/4\varepsilon, & -\varepsilon \leq g_{i} \leq \varepsilon, \\
g_{i}, & g_{i} > \varepsilon
\end{cases} \tag{18}
\]

Then, we introduce a new constraint

\[
g_{i, \varepsilon, \gamma} = -\gamma + \int_{0}^{2} L_{i, \varepsilon}(g(t)) \, dt \leq 0 \tag{19}
\]

where \(\gamma > 0\). By replacing (5), (6), (12) and (13) with (19) in Problem P, we obtain a new problem which is denoted as Problem \(P_{\varepsilon, \gamma}\).

Problem \(P_{\varepsilon, \gamma}\) is an optimal parameter selection problem subject to constraints in the canonical form, which is a nonlinear program and can be solved by the gradient-based method. Particularly, we can use the optimal control software MISER [37, 10] to solve it. However, Problem \(P_{\varepsilon, \gamma}\) is not equivalent to Problem \(P\). \(\varepsilon, \gamma\) have to be adjusted to achieve an optimal solution. We describe this procedure with the following algorithm.

**Algorithm 1.** In this problem, we set \(\varepsilon = 10^{-1}, \gamma = \frac{5\varepsilon}{15}, \varepsilon_{\min} = 10^{3}\).

Step 1: Solve the Problem \(P_{\varepsilon, \gamma}\), and we obtain the optimal solution \(K_{\varepsilon, \gamma}^{*}\).

Step 2: For each \(i\), check the feasibility of \(g_{i}(t) \geq 0\) with \(K_{\varepsilon, \gamma}^{*}\).

Step 3: If all the constraints in Step 2 are satisfied, then go to the Step 5. Otherwise, go to the Step 4.

Step 4: Set \(\gamma = \gamma/2\) and go to Step 1.

Step 5: Set \(\varepsilon = \varepsilon/10, \gamma = \gamma/10\), and go to Step 1.

**Stopping criterion:** Algorithm 1 stops when \(\varepsilon \leq \varepsilon_{\min}\).

**Remark 1.** Since the single-link manipulator is a strong nonlinear system, it is difficult to satisfy the performance specifications with a single group of PID parameters under different situations (initial conditions). In practice, different groups of PID parameters are used for working conditions. In our paper, we only focus on how to tune the PID parameters under a specified condition. For real world application, we may identify the working conditions and then tune the optimal PID parameters according to these conditions. When the working condition changes in practice, the PID parameters are then switched to the group corresponding to that situation.

4. **Gradient formulas for the cost function and the constraints.** For solving Problem \(P_{\varepsilon, \gamma}\), gradient-based method will be used. Therefore, in this section, we shall derive the gradient formulas for the cost function and the constraints in
canonical form. To make the organization of this paper more compact, we omit the proofs. And they are similar to Theorem 4.1 and Theorem 4.2 in [12].

**Theorem 4.1.** The gradient formula of the cost function is
\[
\frac{\partial J(k)}{\partial k} = \int_0^2 \frac{\partial H_0(t, x(t), k, \lambda_0(t))}{\partial k} \, dt
\]  
where \( H_0(t, x(t), k, \lambda_0(t)) \) is the Hamilton function, and
\[
H_0(t, x(t), k, \lambda_0(t)) = [x_1(t) - q_d]^2 + \lambda_0^T(t) f(t, x(t), k)
\]
where \( f \) denotes the right part of (14), and \( \lambda_0(t) \) is the solution of the following co-state equation
\[
\dot{\lambda}_0(t) = - \left[ \frac{\partial H_0(t, x(t), k, \lambda_0(t))}{\partial x} \right]
\]
with the boundary condition
\[
\lambda_0(T) = 0
\]

**Theorem 4.2.** The gradient formula for the constraint function of continuous state inequality is
\[
\frac{\partial L_{i, \varepsilon}(g_i(t))}{\partial k} = \int_0^2 \frac{\partial H_i(t, x(t), k, \lambda_i(t))}{\partial k}, \quad i = 1, 2, 3, 4
\]
where
\[
H_i(t, x(t), k, \lambda_i(t)) = L_{i, \varepsilon}(g_i(t)) + \lambda_i^T(t) f(t, x(t), k)
\]
and \( \lambda_i(t) \) is the solution of the following co-state equations
\[
\dot{\lambda}_i(t) = - \left[ \frac{\partial H_i(t, x(t), k, \lambda_i(t))}{\partial x} \right], \quad i = 1, 2, 3, 4
\]
with the boundary condition
\[
\lambda_i(T) = 0, \quad i = 1, 2, 3, 4
\]

By using gradient-based optimization methods (Theorem 4.1, Theorem 4.2), such as Sequential Quadratic Programming Approximation Scheme [31], these optimal parameter selection problems can be transformed into a nonlinear optimization problem. Therefore, the optimal control software MISER 3.2 can be used.

5. **Numerical simulations.** In this section, the position regulation problem of a single-link manipulator is used to test the effectiveness of the proposed algorithm. The reference input \( q_d \) is a step signal. The parameters in (1) are set as: \( L = 0.25m, g = 9.81, m = 1, \) and \( q_d = 1. \)

By applying Algorithm 1 with MISER 3.2 [10], we obtain \( k_p = 101, k_l = 5 \times 10^{-5}, \) and \( q_d = 1. \) Obviously, it is a PD control since \( k_l \) is almost zero. This is because there is no disturbance in this system and \( k_l \) is for dealing with the steady state error resulted by the disturbance.

We plot the manipulator angle \( q(t) \), angle velocity \( \dot{q}(t) \) and torque of the motor \( \tau(t) \) in Figure 2, Figure 3 and Figure 4, respectively. As shown in Figure 2 - Figure 4, all the continuous state equality constraints are satisfied. In Figure 3, it shows that the angle velocity increases from zero to 12 in a very short time and decreases to zero rapidly. This is because the reference input is a unit step signal.
and manipulator does not move when it is at the desired position. The tongue signal in Figure 4 can also be interpreted similarly.

To test the robustness of the proposed tuning method, we add a disturbance $d = 0.5 \sin(4\pi t)$ between the controller and the manipulator. We plot the manipulator angle $q(t)$, angle velocity $\dot{q}(t)$ and torque of the motor $\tau(t)$ with the same PID parameters under disturbance $d$ in Figure 5, Figure 6 and Figure 7, respectively. Comparing with the curves in Figure 2, Figure 3 and Figure 4, we observe that there are some small oscillations in Figure 5, Figure 6 and Figure 7 due to the disturbance.
The performance specifications are still met, which verify the robustness of our proposed tuning method.

6. Conclusions. In this paper, a control parameterization based optimal PID tuning method is developed. By modelling the performance specifications into the continuous inequality constraints, the problem was an optimal parameter selection problem subject to continuous inequality constraints. We solved this problem by using with the constraint transcription method together with a local smoothing technique. The corresponding gradient formulas for the cost function and the
Constraints were derived, respectively. Simulation results show that our proposed method is effective and robust. For future study, the exact penalty function method could be considered to further improve the performance.

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