A Higher Order Adaptive Approach to Tackle the Swinging Problem

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Abstract: In numerous practical applications precise control of a subsystem passively connected to a precisely controllable subsystem by elastic connection is needed. As typical example is a crane carrying its payload swinging on an elastic string can be mentioned. From the point of view of control technology this task is interesting since the connected degree of freedom has little damping and it is apt to keep swinging accordingly. The traditional approaches apply the input shaping technology to assist the human operator responsible for the manipulation task. In the present paper a novel adaptive approach applying fixed point transformations based iterations having local basin of attraction is proposed for simultaneously tackle the problems originating from the imprecisions of the available dynamic model of the system to be controlled and the swinging phenomenon. In the simulation investigations presented a simple model consisting of two connected mass-points is considered: one of them can directly by controlled by control forces, the other one (in the role of the payload) is dragged by the controlled point via an elastic spring. The control considers the 4th time-derivative of the trajectory of the dragged system.

Keywords: Adaptive Control; Fixed Point Transformations; Cauchy Sequences; Iterative Learning; Local Basin of Attraction

1 Introduction

The control of subsystems passively connected to directly controllable systems by elastic connection of little damping is an interesting task that also has strong practical concern, too. Any payload carried by some crane normally is connected to the directly controllable engine via an elastic string that has very little damping, therefore it is apt to have long-lasting swinging. Precise positioning of the swinging bodies traditionally is solved by the so-called "input shaping approach" that goes back to the nineties of the past century. The main idea of input shaping is the generation command signals that can efficiently reduce payload oscillations by slightly modifying the operator's command by convolving it with a series of impulses [1], [2]. This technique can cancel out the system's own motion-induced oscillations. It was successfully used to reduce transient and residual oscillation in various systems, e.g. in coordinate measuring machines [3], and even recently in various cranes [4], [5], [6], [7]. The positive effect of this technique has been shown in the reduction of task completion time and obstacle collisions in a number of crane operator performance studies. It is a present trend to further improve operator performance by assisting crane operators in the estimation of the crane's stopping location. From mathematical point of view this technique is strictly related to linear systems and linear approximation of nonlinear ones as well as to linear control solutions (e.g. [8]).

An alternative approach to this problem may be the simultaneous tackling of the imprecisions of the available dynamic model of the system to be controlled and the swinging problem. The most sophisticated adaptive control elaborated for robots is the Slotine-Li controller [9] that tries to learn certain parameters of the dynamic model using Lyapunov's 2nd Method. It has the main deficiency that it is unable to compensate the effects of lasting unknown external perturbations [10], and is unable to identify the parameters of strongly nonlinear phenomena as friction for which sophisticated techniques have to be applied (e.g. [11]). Furthermore, due to insisting on the use of the Lyapunov function technique the order of the ordinary differential equations to be handled by this method is limited to 2. For getting rid of the formal restrictions that normally originate from the use of Lyapunov functions alternative possibilities were considered for developing adaptive controllers. In [12] the mathematical model of the system to be controlled was considered as a mapping between its *desired* and *realized responses* in which the *desired response* was calculated on purely kinematical basis, and the appropriate excitation to obtain this response was computed by the use of a partial and approximate dynamic model of the system, while the *realized response* was measured. It was shown that in this approach the "*response*" of the system may be arbitrary order derivative of the state variables, it can be even a fractional order one. Its robust variant was successfully applied even for a strongly nonlinear system as e.g. the Van der Pol Oscillator [13]. The essence of this method is obtaining a convergent iteration using contractive mapping in Banach spaces, and to some extent it is akin to other iterative approaches as e.g. iterative tuning techniques (e.g. [14]). Its details are considered in the next section.

2 The Excitation - Response Scheme and Fixed Point Transformations

Several control tasks can be formulated by using the concepts of the appropriate "excitation" $\mathbf{Q}$ of the controlled system to which it is expected to respond by some prescribed or "desired response" $\mathbf{r}^d$. The appropriate excitation can be computed by the use of some inverse dynamic model $\mathbf{Q} = \varphi\left(\mathbf{r}^d\right)$. Since normally this inverse model is neither complete nor exact, the actual response determined by the system's dynamics, ψ, results in a *realized response* $\mathbf{r}^r$ that differs from the desired one: $\mathbf{r}^r = \phi\left(\varphi\left(\mathbf{r}^d\right)\right) := \mathbf{f}\left(\mathbf{r}^d\right)$. It is worth noting that these functions may contain various hidden parameters that partly correspond to the dynamic model of the system, and partly pertain to unknown external dynamic forces acting on it. Due to phenomenological reasons the controller can manipulate or "deform" the input value from $\mathbf{r}^d$ so that $\mathbf{r}^d = \mathbf{f}\left(\mathbf{r}_*^d\right)$. Other possibility is the manipulation of the output of the rough model as $\mathbf{r}^d = \phi\left(\varphi_*\left(\mathbf{r}^d\right)\right)$. In the sequel it will be shown that for *SISO* systems the appropriate deformation can be defined as some *Parametric Fixed Point Transformation*. The latest version elaborated for SISO systems was the function

$$G\left(r;r^d\right) = \left(r+K\right)\left[1+B\tanh\left(A\left[f\left(r\right)-r^d\right]\right)\right]-K \tag{1}$$

with the following properties: if $f(r_*)=r^d$ then $G(r_*,r^d)=r_*$, $G(-K,r^d)=-K$, and

$$G' = \left(r+K\right)\frac{BAf'\left(r\right)}{\cosh^2\left(A\left[f\left(r\right)-r^d\right]\right)} + \left[1+B\tanh\left(A\left[f\left(r\right)-r^d\right]\right)\right] \tag{2}$$

that can be made contractive in the vicinity of r_* by properly setting the parameters A, B, and K, in which case the iterative sequence $r_{n+1}=G(r_n,r^d)\to r_*$ as $n\to\infty$. The saturated nonlinear behavior of the *tanh* function played very important role in (1). The generalization of (1) for *Multiple Input – Multiple Output* (*MIMO*) systems may be done in different manners. A possibility is the use of the norm for the system-response $\|\mathbf{r}\| = \sum_i |r_i|$, and a multiple dimensional sigmoid function in the role of the *tanh* function as $\boldsymbol{\sigma}(\mathbf{r}): \Re^n \to \Re^n$ as $y_i = \sigma^{(i)}\left(r_i\right)$ in which each function $\sigma^{(i)}(\ )$ is a single-dimensional sigmoid. If each of them is contractive, i.e. $\forall i\ \exists 0 \le M_i < 1$ so that $\left|\sigma^{(i)}(a) - \sigma^{(i)}(b)\right| \le M_i |a-b|$ then

$$\begin{aligned}&\|\boldsymbol{\sigma}(\mathbf{a})-\boldsymbol{\sigma}(\mathbf{b})\| := \sum_i \left|\sigma^{(i)}(a_i)-\sigma^{(i)}(b_i)\right| \le \sum_i M_i |a_i - b_i| \le \\ &\le \underset{i}{Max}\{M_i\}\sum_i |a_i - b_i| = M\|\mathbf{a}-\mathbf{b}\|,\ 0 \le M < 1\end{aligned} \tag{3}$$

that means that this multiple dimensional sigmoid function is contractive in a Banach space. In this case it is possible to find the A_i, B_i, and K_i control parameters for each component i. An alternative possibility is to define the *response error* and its *direction* in the n^{th} control step as $\mathbf{h}_n = \mathbf{f}(\mathbf{r}_n) - \mathbf{r}^d$, $\mathbf{e}_n := \mathbf{h}_n / \|\mathbf{h}_n\|$, and apply the following transformation:

$$\text{if } \|\mathbf{h}_n\| > \varepsilon \text{ then } \mathbf{x}_{n+1} = \left(1+\tilde{B}\right)\mathbf{x}_n + \tilde{B}K\mathbf{e} \text{ else } \mathbf{x}_{n+1} = \mathbf{x}_n,\ \tilde{B} := B\sigma\left(A\|\mathbf{h}_n\|\right), \tag{4}$$

in which ε is a small positive threshold value for the response error. If the response error is quite small, the system already attained the fixed point and no any manipulation is needed with the unit vector the computation of which would be singular. In the case of this implementation we have four control parameters, ε, A, B, and K, and a single sigmoid function $\sigma()$. This realization applies correction in the direction of the response error, and normally leads to more precise tracking than the more complicated one using separate control parameters for various directions. In the sequel this realization will be applied for the swinging reduction problem. The command signal given to the model-based controller will be referred to as "*required*" signal. In the non-adaptive case the "*required*" and "*desired*" values are equal to each other, while in the adaptive case they differ from each other according to the adaptive law coded in (4).

3 The Swinging Problem as Higher Order Control Task

Let us consider the very simple model of two mass-points connected by a spring of stiffness k and zero force length L_0. The motion of mass point A of mass m_A and coordinates $\mathbf{x}$ has to be controlled by directly applying forces to mass point B of mass m_B and coordinates $\mathbf{y}$. The equations of motion of this system is given as

$$\begin{aligned}m_A\ddot{\mathbf{x}} &= -\mu_A\dot{\mathbf{x}} + \frac{\mathbf{y}-\mathbf{x}}{\|\mathbf{y}-\mathbf{x}\|}\left(\|\mathbf{y}-\mathbf{x}\| - L_0\right) + m_A\mathbf{g}_{grav} \\ m_B\ddot{\mathbf{y}} &= -\mu_B\dot{\mathbf{y}} - \frac{\mathbf{y}-\mathbf{x}}{\|\mathbf{y}-\mathbf{x}\|}\left(\|\mathbf{y}-\mathbf{x}\| - L_0\right) + m_B\mathbf{g}_{grav} + \mathbf{u}\end{aligned}, \tag{5}$$

in which μ_A and μ_B are viscous damping coefficients, $\mathbf{g}_{grav}$ denotes the gravitational acceleration, and $\mathbf{u}$ is the active force that can be used for control purposes, the ||**x**|| symbol denotes the Frobenius norm. In a more general form (5) can be written as

$$\ddot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \dot{\mathbf{x}}, \mathbf{y}), \quad \ddot{\mathbf{y}} = \mathbf{g}(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{x}, \mathbf{u}) \tag{6}$$

from which it follows that the 2nd time-derivative of **x** cannot be instantaneously set by the control force **u**. It is evident that we have to derive the 1st equation of the group (6) two times according to time to make $\ddot{\mathbf{y}}$ appear in it. According to the "chain rule" the following set of equations has to be considered:

$$\mathbf{x}^{(4)} = \tilde{\mathbf{f}}(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \dddot{\mathbf{x}}, \mathbf{y}, \dot{\mathbf{y}}, \ddot{\mathbf{y}}), \quad \dddot{\mathbf{x}} = \hat{\mathbf{f}}(\mathbf{x}, \dot{\mathbf{x}}, \ddot{\mathbf{x}}, \mathbf{y}, \dot{\mathbf{y}}), \quad \ddot{\mathbf{y}} = \mathbf{g}(\mathbf{y}, \dot{\mathbf{y}}, \mathbf{x}, \mathbf{u}) \tag{7}$$

that means that the desired 4th time-derivative of **x** can be prescribed and related to $\ddot{\mathbf{y}}$, that is to the control force. Practically, by using the 1st and 2nd equations of (7) for a *desired* $\mathbf{x}^{(4)D}$ a *desired* $\ddot{\mathbf{y}}^D$ can be constructed for which, from the 3rd equation a control force can be computed. Regarding the construction of $\mathbf{x}^{(4)D}$ it is reasonable that human operators can well estimate position and velocity on the basis of optical observations but cannot well estimate acceleration and higher derivatives. However, by measuring the deformation of microscopic components efficient acceleration sensors are available in our days. Via numerical derivation of their signal the third and 4th time-derivatives of the coordinates become available. In the forthcoming simulations the simple trajectory tracking strategy

$$0 = \left(\frac{d}{dt} + \Lambda\right)^4 \left(\mathbf{x}^N - \mathbf{x}\right) = \sum_{l=0}^{4} \frac{4!}{l!(4-l)!} \Lambda^l \left(\frac{d}{dt}\right)^{4-l} \left(\mathbf{x}^N - \mathbf{x}\right) \tag{8}$$

was applied for a positive constant parameter Λ. In general similar command can be constructed if we assume that the nominal trajectory is planned in advance, and the 0th and 1st order corrections originate from the human operator and the additional higher order ones come from the controller. In the sequel simulation results will be presented. It is important to note that in the simulations only 2nd order equations are numerically integrated, the 4th derivatives of **x** occur only in the control law.

4 Simulation Results

In the simulations the *exact parameters* of the system model were m_A=1, m_B=2 *kg*, μ_A=10, μ_B=20 *Ns/m*, *k*=100 *N/m*, L_0=1 *m*, while their estimated values used by the controller were $m_{A\_}$=0.8, $m_{B\_}$=2.3 *kg*, $\mu_{A\_}$=15, $\mu_{B\_}$=18 *Ns/m*, *k_*=110 *N/m*, $L_{0\_}$=1.2 *m*. The adaptive control parameters were $K=-3.2\times10^4$, *B*=1, $A=2\times10^{-6}$, $\mathbf{g}_{grav}$ had the value of 10 m/s^2 in the $-x_2$ direction. The nominal trajectory consisted of constant 3rd derivative, constant acceleration, and constant velocity segments.

The simulations made for the non-adaptive controller soon became divergent. In Fig. 1 only the initial phase of the so obtained motion can be traced. It can be seen that the "*desired*" and the "*required*" 4th time-derivatives are identical and they considerably differ from the realized values.

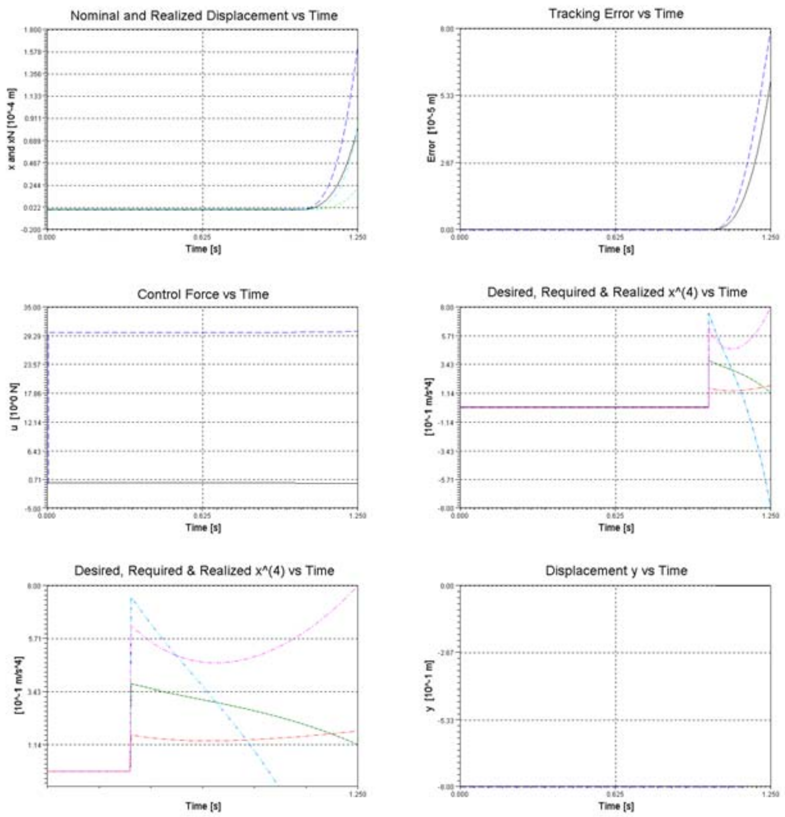

Figure 1

The operation of the non-adaptive control: x_1^N (black solid), x_2^N (blue dashed), x_1 (green with dense dashes), x_2 (light blue dash-dot); for the tracking errors: x_1^N- x_1 (black solid), x_2^N- x_2 (blue dashed); for the control forces: u_1 (black solid), u_2 (blue dashed); for the 4th time-derivatives: $x_1^{(4)D}$ (black solid), $x_2^{(4)D}$ (blue dashed), $x_1^{(4)Req}$ (green with dense dashes), $x_2^{(4)Req}$ (light blue dash-dot), $x_1^{(4)}$ (red dash-dot-dot), $x_2^{(4)}$ (magenta dash-dot); for the displacement of the directly controlled mass point: y_1 (black solid), y_2 (blue dashed)

The variation of the control forces is very slow, and the displacement of the driven mass-point is almost negligible. This behavior well mirrors the expected property that the system has a kind of long term memory because considerable time is needed for the displacement of the directly driven body to result in considerable deformation of the elastic link that can exert considerable driving force on the indirectly controlled body.

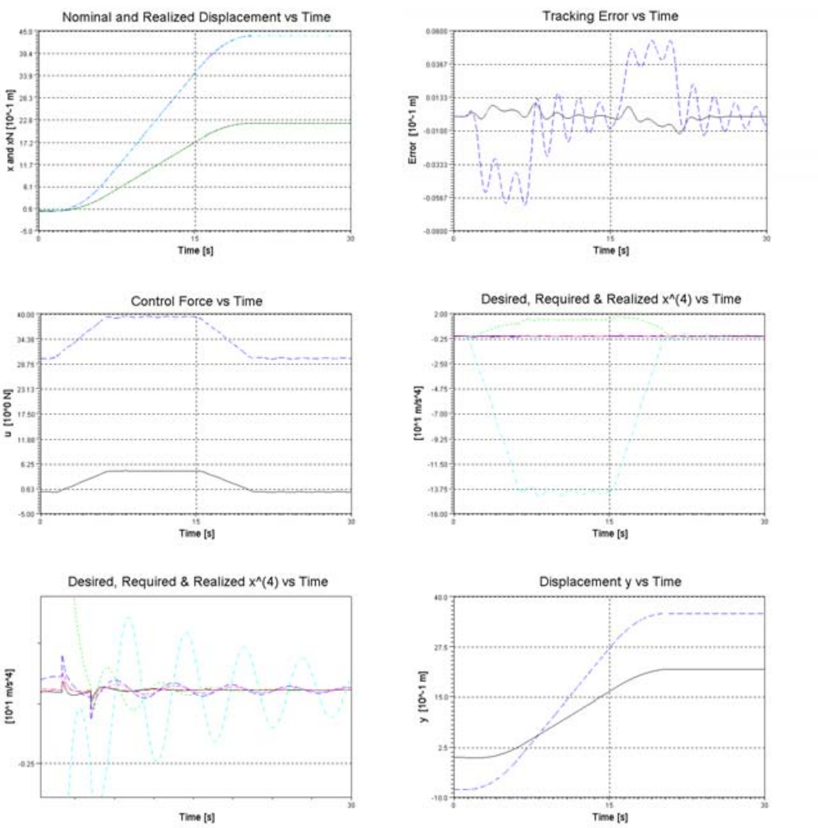

Figure 2

Operation of the adaptive controller; for the trajectories: x_1^N (black solid), x_2^N (blue dashed), x_1 (green with dense dashes), x_2 (light blue dash-dot); for the tracking errors: x_1^N- x_1 (black solid), x_2^N- x_2 (blue dashed); for the control forces: u_1 (black solid), u_2 (blue dashed); for the 4th time-derivatives: $x_1^{(4)D}$ (black solid), $x_2^{(4)D}$ (blue dashed), $x_1^{(4)Req}$ (green with dense dashes), $x_2^{(4)Req}$ (light blue dash-dot), $x_1^{(4)}$ (red dash-dot-dot), $x_2^{(4)}$ (magenta dash-dot); for the displacement of the directly controlled mass point: y_1 (black solid), y_2 (blue dashed)

The adaptive counterpart of Fig. 1 is Fig. 2 that reveals precise trajectory tracking and considerable adaptive deformation of the input (the "*required*") signal. In this case the deformed "*required*" 4th time derivatives significantly differ from the "*desired*" ones that well agree with the "*realized*" values. In both of the charts describing the 4th derivatives and the control forces the controller's effort to compensate swinging phenomena can well be traced. Due to this compensation effect the displacement of the bodies remains free of any swinging. (Only small components of swinging can be traced in the charts describing the tracking errors.)

Conclusions

In this paper a possible application of a fixed point transformation based iterative control was studied for tackling the swinging problem that normally occur when various payloads are carried by cranes using elastic wires/ropes to realize mechanical connection between the cranes and their burden. In this application there is a possibility to apply a purely kinematically designed tracking policy that partly can originate from the human operator, and partly from the sensor system. The simulation results here presented are promising. In the next step more extended simulations have to be done in which the role of the directly controlled mass-point the crane as a more complex connected subsystem can be present. Earlier investigations foster the expectation that a similar, simple control approach can successfully work for such a more complex, dynamically coupled system, too.

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