Equivalence between Approximate Dynamic Inversion and Proportional-Integral Control

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Abstract— **Approximate Dynamic Inversion is a method applicable to control of minimum phase, nonaffine-in-control systems. We show that if all the system states are available for feedback, the Approximate Dynamic Inversion controller can be realized as a *linear* Proportional-Integral *model reference* controller without knowledge of the nonlinear system beyond the sign of the control effectiveness, and without any approximations. Similarities with earlier work on high-gain feedback and variable structure control of *affine-in-control* nonlinear systems are highlighted, which suggests a possible link between Approximate Dynamic Inversion and variable structure control for nonaffine-in-control systems.**

I. Introduction

In [1], [2], the authors laid the foundation for a method of Approximate Dynamic Inversion (ADI) for a class of minimum phase, nonaffine-in-control systems, assuming known system dynamics. The method is founded on the time-scale separation principle from singular perturbation theory [3, Chapter 11], where the control is defined as a solution of "fast" dynamics. The ADI control law as originally formulated depends on the nonlinear function that describes the system. When this function is known, implementation of the ADI controller is straightforward. When this function is unknown, one plausible way would be to estimate this function and construct an analogous ADI control law based on that estimate [4], [5]. We show that with full state feedback, and knowledge of the sign of the control effectiveness, the ADI controller can be implemented exactly as a Proportional-Integral (PI) *model reference* controller. This eliminates the need for any approximation of the plant dynamics to realize the ADI controller.

It will be apparent that the resulting PI control is a high-gain controller given that the controls have fast dynamics as required of the ADI method. Given these results, it is of interest to observe the similarities with earlier work on high-gain control and variable structure control of affine-in-control systems [6].

The rest of the paper is organized as follows. Section II outlines the ADI method. For single-input systems, section III shows that every ADI control law has a PI controller realization, and section IV discuss a few variants of ADI control. Simulation results comparing an ADI variant to a PI implementation is presented in section V. The final section highlights some similarities to earlier work on high-gain control and variable structure control, suggesting a possible link between the ADI method and variable structure control of nonaffine-in-control systems.

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II. Background

For the purposes of this paper, the ADI method is outlined here for single-input systems, and all but the bare essentials are omitted. The reader is referred to [1], [2] for a complete presentation, proofs and technical details.

Let the system to be controlled be an n-th order, single input, minimum phase, nonaffine-in-control system expressed in *normal form* [3, Section 13.2]

$$\dot{x}(t) = Ax(t) + Bf(x(t), u(t)), \qquad x(0) = x_0, \quad (1)$$

where $x(t) = [x_1(t), x_2(t), \dots, x_n(t)]^{\mathrm{T}} \in \mathbb{R}^n$ is the state of the system, $u(t) \in \mathbb{R}$ is the control, $f(x(t), u(t))$ is (in general) a nonlinear function of the state and control, and A, B have the form

$$A = \begin{bmatrix} 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \\ 0 & 0 & \dots & 0 \end{bmatrix}, \qquad B = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}. \quad (2)$$

It is desired for $x(t)$ to track the states of a *stable* n-th order linear reference model described in the controllable canonical form

$$\dot{x}_r(t) = A_r x_r(t) + B_r r(t), \qquad x_r(0) = x_{r0}, \quad (3)$$

where $x_r(t) = [x_{r1}(t), x_{r2}(t), \dots, x_{rn}(t)]^{\mathrm{T}} \in \mathbb{R}^n$ is the state of the reference model, $r(t) \in \mathbb{R}$ is the reference input, and A_r, B_r have the form

$$A_r = \begin{bmatrix} 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \\ -a_{r1} & -a_{r2} & \dots & -a_{rn} \end{bmatrix}, \quad B_r = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ b_r \end{bmatrix}. \quad (4)$$

Define the tracking error as

$$e(t) = x(t) - x_r(t), \quad (5)$$

where $e(t) = [e_1(t), e_2(t), \dots, e_n(t)]^{\mathrm{T}} \in \mathbb{R}^n$ and $e_i(t) = x_i(t) - x_{ri}(t)$ for $i \in \{1, 2, \dots, n\}$. The ADI control law in [2] is reproduced below

$$\epsilon \dot{u}(t) = -\operatorname{sign}\left(\frac{\partial f}{\partial u}\right)\left(f(e(t) + x_r(t), u(t)) + \sum_{i=1}^{n} a_{ri}\big(e_i(t) + x_{ri}(t)\big) - b_r r(t)\right), \quad (6)$$

with $u(0) = u_0$. Here, ϵ is a design parameter, chosen sufficiently small so that the controller dynamics are fast enough to approximately achieve dynamic inversion. For some insight into (6), observe that exact dynamic inversion is achieved when the controls, $u(t)$, satisfy $f(e(t) + x_r(t), u(t)) + \sum_{i=1}^{n} a_{ri}\big(e_i(t) + x_{ri}(t)\big) - b_r r(t) = 0$. In essence, (6) relaxes the requirement for strict dynamic inversion while increasing the control in a direction that drives this discrepancy to zero. In [2], it is assumed that some control authority always exist, ie. $|\frac{\partial f}{\partial u}| \geq b_0 \gg 0$. This implies that the sign of the control effectiveness, $\text{sign}\big(\frac{\partial f}{\partial u}\big) \in \{-1, 1\}$, is a constant. Let $\text{sign}\big(\frac{\partial f}{\partial u}\big) = \alpha$ for notational convenience.

III. Proportional-Integral Controller Realizations

Observe that using (5), the ADI control law (6) can be rewritten as

$$\epsilon \dot{u}(t) = -\alpha\Bigg(f(x(t), u(t)) + \sum_{i=1}^{n} a_{ri} e_i(t) - \Big(-\sum_{i=1}^{n} a_{ri} x_{ri}(t) + b_r r(t) \Big) \Bigg).$$

Using the last row of (4) in the above yields

$$\epsilon \dot{u}(t) = -\alpha\Bigg(f(x(t), u(t)) + \sum_{i=1}^{n} a_{ri} e_i(t) - \dot{x}_{rn}(t) \Bigg),$$

and using (1) and (2) gives

$$\begin{aligned}\epsilon \dot{u}(t) &= -\alpha\Bigg(\dot{x}_n(t) - \dot{x}_{rn}(t) + \sum_{i=1}^{n} a_{ri} e_i(t) \Bigg) \\ &= -\alpha\Bigg(\dot{e}_n(t) + \sum_{i=1}^{n} a_{ri} e_i(t) \Bigg).\end{aligned}$$

The states of the reference model $x_r(t)$ can be easily obtained by simulation. If the system states $x(t)$ are available for feedback, the error $e(t)$ is easily computed, and the control law can be implemented as

$$u(t) = -\frac{\alpha}{\epsilon}\left(e_n(t) + g(t, e(t)) \right), \tag{7a}$$

where

$$g(t, e(t)) = \int_0^t \sum_{i=1}^{n} a_{ri} e_i(\tau)\, d\tau, \tag{7b}$$

$$g(0, e(0)) = -e_n(0) - \epsilon\alpha u_0. \tag{7c}$$

Note that (7c) is to recover the initial control $u(0) = u_0$. It can be seen that the result is a PI controller acting on the error between the system states and the states of the reference model. Note that (7) is written in a way to highlight the PI structure that acts on some error. In reality, it can be implemented in an even simpler way without simulating the reference model by

$$u(t) = -\frac{\alpha}{\epsilon}\left(x_n(t) + h(t, x(t), r(t)) \right) \tag{8a}$$

where

$$h(t, x(t), r(t)) = \int_0^t \left(\sum_{i=1}^{n} a_{ri} x_i(\tau) - b_r r(\tau) \right) d\tau, \tag{8b}$$

$$h(0, x(0), r(0)) = -x_n(0) - \epsilon\alpha u_0.$$

Additionally, observe that from (1)–(5), the following holds

$$\int_0^t x_i(\tau)\, d\tau = x_{i-1}(t) - x_{i-1}(0) \tag{9}$$

$$\int_0^t e_i(\tau)\, d\tau = e_{i-1}(t) - e_{i-1}(0) \tag{10}$$

for $i \in \{2, 3, \ldots, n\}$. These relations used only information from the structure of the system descriptions and no explicit information about the system. Using (9), controller (8) can be rewritten as

$$u(t) = -\frac{\alpha}{\epsilon}\Bigg(x_n(t) + \sum_{i=1}^{n-1} a_{r(i+1)} x_i(t) + p(t, x(t), r(t)) \Bigg), \tag{11a}$$

where

$$p(t, x(t), r(t)) = \int_0^t \big(a_{r1} x_1(\tau) - b_r r(\tau) \big)\, d\tau \tag{11b}$$

$$p(0, x(0), r(0)) = -x_n(0) - \sum_{i=1}^{n-1} a_{r(i+1)} x_i(0) - \epsilon\alpha u_0.$$

An analogous form of (11) in the error coordinates can be similarly written by using (10). Observe that even without explicit knowledge of the nonaffine-in-control function $f(x(t), u(t))$, controllers (7), (8) and (11) can be implemented exactly without any approximations if the sign of the control effectiveness, $\text{sign}\big(\frac{\partial f}{\partial u}\big) = \alpha$, is known.

The preceding establishes that every ADI control law admits a PI controller realization. The significance lies in enabling new interpretations and/or ways of analyzing the ADI and PI control. In section VI, controller (11) will be used to highlight some similarities with earlier work on high-gain state feedback and variable structure control of affine-in-control nonlinear systems [6].

IV. Variants of Approximate Dynamic Inversion Control

In this section, we discuss three variants of the ADI method, and point out that, as a consequence of the existence of an exact PI controller realization, two of the variants appear to be unnecessary.

A. Known Dynamics

A variant of the original ADI control law is presented in [7] assuming full knowledge of the system. This control law is

$$\epsilon \dot{u}(t) = -\left(\frac{\partial f}{\partial u}(x(t), u(t)) \right) \Bigg(f(x(t), u(t)) + \sum_{i=1}^{n} a_{ri}\big(e_i(t) + x_{ri}(t)\big) - b_r r(t) \Bigg).$$

This variant uses significantly more information about the system through $\frac{\partial f}{\partial u}(x(t), u(t))$ in contrast to $\text{sign}(\frac{\partial f}{\partial u})$. In this case, the PI realization does not apply. This method has been applied to a nonaffine-in-control double inverted pendulum in [8].

B. Indirect Adaptive Control

In [4], [5], the original ADI method in [2] is extended for the case where the system dynamics are unknown. In this scheme, a stable observer is used to train a Radial Basis Function (RBF) Neural Network (NN), which in turn is used to estimate the unknown nonlinear function $f(x(t), u(t))$ in (6). This estimate is then used to construct a control law that is analogous to (6). As noted above, if all the system states are available for feedback, and the sign of the control effectiveness is known, the exact controller can be implemented without any further knowledge of $f(x(t), u(t))$ or any approximations. These conditions are precisely satisfied by the assumptions in [5]. Hence the RBF NN and the observer used to train it do not appear to be essential. Refs. [9]–[11] further apply this method to other problems but without significant alterations to the formulation.

C. Direct Adaptive Control

Ref. [12] presents a direct adaptive control variant to [5] in which no reference models are used, but requires a bounded n times continuously differentiable reference signal and all its i^{th}, $i \in \{1, 2, \ldots, n-1\}$ time derivatives to be available for feedback. In this case, a PI realization for the adaptive augmentation control law can be derived in an analogous manner. Under the assumptions made, it also appears that this adaptive scheme is not necessary. Numerical examples in [13] shows that the PI realization achieves/exceeds the tracking performance of this adaptive scheme.

V. Simulations

This section uses the Van der Pol oscillator example in [10] to compare the RBF NN based design with the simplified PI controller implementation (8), where only $\text{sign}(\frac{\partial f}{\partial u})$ is assumed to be known, and all system states are available for feedback. The model of the Van der Pol oscillator is

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= -x_1 + \left(1 - x_1^2\right) x_2 + \tanh(x_1 + u + 3) \\ &\qquad\qquad\qquad + \tanh(u - 3) + 0.01u, \end{aligned}$$

and the reference model is specified with

$$A_r = \begin{bmatrix} 0 & 1 \\ -2 & -3 \end{bmatrix}, \qquad B_r = \begin{bmatrix} 0 \\ 2 \end{bmatrix}.$$

It is clear that $\text{sign}(\frac{\partial f}{\partial u}) = 1$. The controller parameter ϵ is chosen to be 0.02 as in [10], and the initial condition is set as $u_0 = 0$. This specifies the PI controller (8) completely. The additional parameters related to the NN and state observer for the RBF NN based design is identical to that stated in [10] and will not be repeated here.

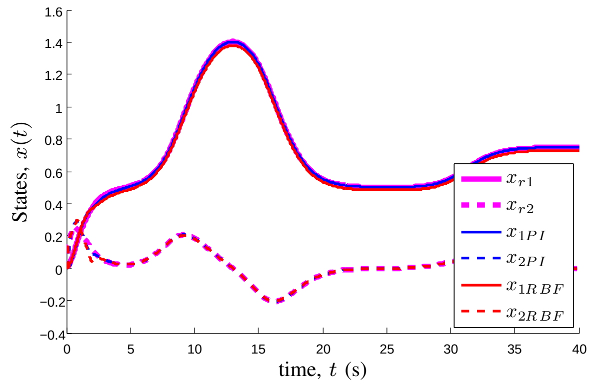

Fig. 1. System States and Reference Model States for $r(t) = r_a(t)$

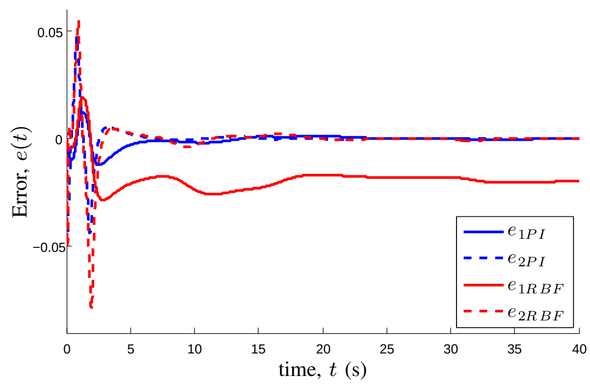

Fig. 2. State Errors for $r(t) = r_a(t)$

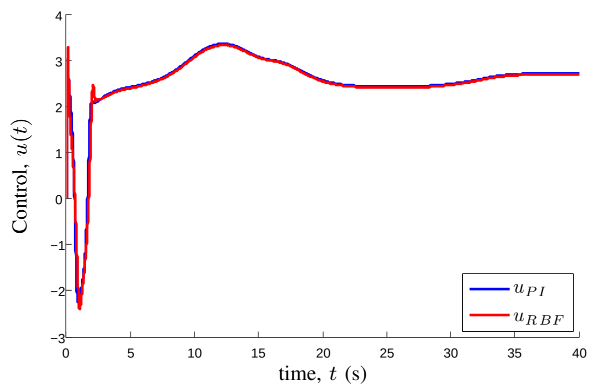

Fig. 3. Control Signal for $r(t) = r_a(t)$

For a reference command $r(t) = r_a(t)$,

$$r_a(t) = -\frac{1}{1+e^{t-8}} + \frac{1}{1+e^{t-15}} - \frac{1}{4\left(1+e^{t-30}\right)} + \frac{3}{4},$$

the results are shown in Fig. 1, 2 and 3.

For a reference command $r(t) = r_b(t)$

$$r_b(t) = \sin(2\pi t),$$

the results are shown in Fig. 4, 5 and 6. The system states, state error, and control signal using the controller (8) are labeled with subscript "PI", and those generated with the RBF NN implementation are labeled with subscript "RBF". Fig. 1 and 4 show the system states using both controllers, together with the states of the reference model for $r(t) = r_a(t)$ and $r(t) = r_b(t)$ respectively. Fig. 2 and 5 show

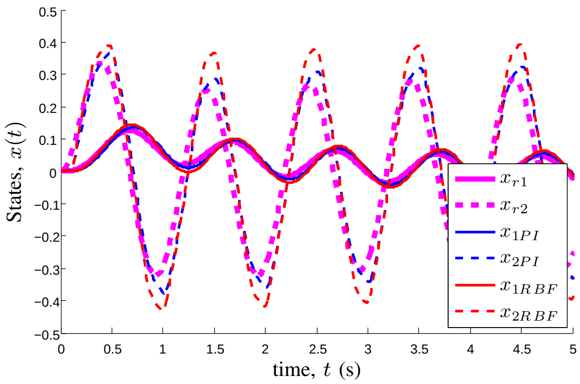

Fig. 4. System States and Reference Model States for $r(t) = r_b(t)$

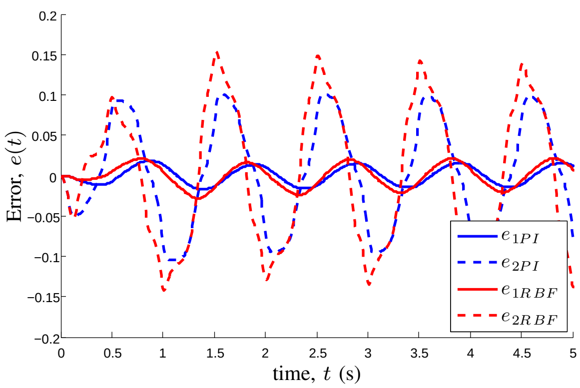

Fig. 5. State Errors for $r(t) = r_b(t)$

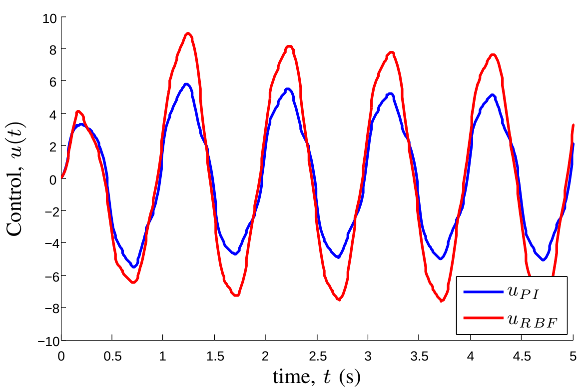

Fig. 6. Control Signal for $r(t) = r_b(t)$

the state errors as defined by (5). Fig. 3 and 6 show the corresponding control signals.

It is clear that in both cases, the PI implementation has better tracking performance. In Fig. 2, observe that using the RBF NN implementation, e_{1RBF} has a non-zero steady state error, while e_{1PI} and e_{2PI} both converge to zero as $t \to \infty$. In Fig. 5, observe that the amplitude of e_{2RBF} is larger than that of e_{2PI}. Furthermore, as seen in Fig. 6, the amplitude of u_{RBF} is larger than that of u_{PI}. In summary, the PI controller achieves/exceeds the tracking performance of the RBF NN implementation.

Note that Theorem 2 in [1] states that for some $T > 0$, the error vector satistfy $e(t) = O(\epsilon)$ for $t \in [T, \infty)$. In other words, no asymptotic convergence of the error to zero is guaranteed. Numerical results in Fig. 5, which shows that $e_{iPI}(t)$ is oscillating and $e_{iPI}(t) = O(\epsilon) = O(0.02)$ for $t > 0$, $i \in \{1, 2\}$, is thus consistent with the theorem.

VI. Similarities with High-Gain State Feedback and Variable Structure Control

Having established equivalence between the ADI method and high-gain PI control, we highlight some similarities to earlier work on high-gain state feedback and variable structure control for *affine-in-control* nonlinear systems. In [6], the author used singular perturbation techniques to analyze these two control strategies for *affine-in-control* single-input nonlinear systems

$$\dot{x}(t) = f(x) + g(x)u(t), \qquad x(t) \in \mathbb{R}^n, \tag{12}$$

and in particular, addressed their use in feedback-linearizable systems.

Here, the high-gain feedback strategy is outlined. The system is first transformed by an appropriate change of coordinates to $\tilde{x}(t) = [\tilde{x}_1(t), \ldots, \tilde{x}_n(t)]^{\mathrm{T}}$ such that the control appears only in the n^{th} state differential equation, resulting in the transformed system

$$\begin{aligned} \dot{\tilde{x}}_1(t) &= \tilde{f}_1(\tilde{x}(t)) \\ \dot{\tilde{x}}_2(t) &= \tilde{f}_2(\tilde{x}(t)) \\ &\vdots \\ \dot{\tilde{x}}_n(t) &= \tilde{f}_n(\tilde{x}(t)) + \tilde{g}_n(\tilde{x}(t))u(t). \end{aligned} \tag{13}$$

The function $\tilde{g}_n(\tilde{x}(t))$ and each of $\tilde{f}_i(\tilde{x}(t))$, $i \in \{1, 2, \ldots, n\}$ are obtained as the *Lie derivative* [3, pp. 509 – 510] of the transformation functions $\tilde{x}_i(t) = \phi_i(x(t))$ with respect to $g(x)$ and $f(x)$ in (12) respectively. The high-gain control considered is

$$u(t) = \frac{1}{\epsilon} \operatorname{sign}\big(\tilde{g}_n(\tilde{x}(t))\big)\big(u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t)) - \tilde{x}_n(t)\big), \tag{14}$$

where ϵ is a small parameter and $u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t))$ has to be designed according to some desired "slow" reduced dynamics. Tikhonov's theorem [3, pp. 434] is then invoked to show that the "fast" dynamics reaches the equilibrium manifold

$$\Omega = \{\tilde{x}(t) \in \mathbb{R}^n : \tilde{x}_n(t) = u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t))\}$$

for all initial conditions.

Next, it is shown in [6] that the "slow" or averaged dynamics of the system using variable structure control (also known as sliding mode control [3, Section 14.1]), where the sliding manifold is defined by

$$w(\tilde{x}(t)) = \tilde{x}_n(t) - u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t)) = 0,$$

coincides with that using the high-gain state feedback in (14). This establishes the equivalence between high-gain state feedback and variable structure control with regards to the "slow" dynamics.

Ref. [6] then considered feedback linearizable systems which can be transformed to the form of (13) with the property that $\tilde{f}_i(\tilde{x}(t)) = \tilde{x}_{i+1}(t)$ for $i \in \{1, 2, \ldots, n - 1\}$. It was shown that, by using high-gain state feedback or variable structure control, such systems can be approximately transformed into linear systems of order $n - 1$. In other words, one can approximately achieve dynamic inversion for affine-in-control nonlinear systems while losing one degree of freedom. The disadvantage of such approaches, as pointed out in [6], is that $\tilde{x}_n(t)$ cannot be controlled arbitrarily, but regulated to the value $u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t))$.

Observe the many similarities between the high-gain state feedback strategy and the PI control of section III. By starting off in normal form as in (1), (2), the system was implicitly assumed to be feedback linearizable and the coordinate transformation was applied apriori. It is easily seen that the transformed system of (13) with $\tilde{f}_i(\tilde{x}(t)) = \tilde{x}_{i+1}(t)$ for $i \in \{1, \ldots, n - 1\}$ is a specialization of (1) and (2) for affine-in-control systems. The similarities between (11) and (14) are also striking. In (14), $\mathrm{sign}\big(\tilde{g}_n(\tilde{x}(t))\big)$ is the sign of the control effectiveness, and ϵ has the same meaning as a control parameter, chosen sufficiently small to achieve sufficiently fast controls. Comparing (11) and (14), a function analogous to $u_s(\tilde{x}_1(t), \ldots, \tilde{x}_{n-1}(t))$ in (14) can be defined for the high-gain PI controller, but in this case, it is fully specified by the linear reference model (3) and (4).

While no explicit relation is shown in this paper, the similarities highlighted suggests a possible link between high-gain PI control, and high-gain state feedback for nonlinear systems. The equivalence between ADI control and PI control established in this paper, and the equivalence between high-gain state feedback and variable structure control of affine-in-control systems established in [6], then suggest a possible link between the ADI method and variable structure control for nonaffine-in-control systems.

VII. Conclusion

If full state feedback is available, the Approximate Dynamic Inversion control law in [2] can be integrated to yield a *linear* PI controller. This controller can be implemented exactly without knowledge of the nonlinear function beyond the sign of the control effectiveness.

The main objective of this paper is to show that every ADI control law admits a PI controller realization. This links a fairly general control design method to a very simple implementation, and would have great appeal to practitioners seeking a method to control minimum phase, nonaffine-in-control systems.

Similarities to early work on high-gain state feedback and variable structure control of affine-in-control systems were also highlighted. These suggests a possible link between Approximate Dynamic Inversion and variable structure control of nonaffine-in-control systems.

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