Orbital Research Inc.

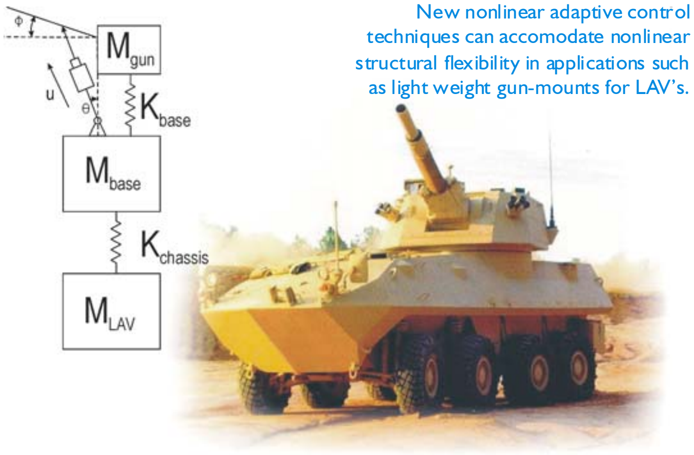
ADAPTIVE NONLINEAR CONTROL

Nonlinear control techniques for global regulation of underactuated systems

Recent research into the development of systematic design for global adaptive control of nonlinear systems with parametric uncertainty at Case Western Reserve University has resulted in the development of a nonsmooth framework for global adaptive control of a significant class of nonlinearly parameterized systems. Orbital Research, Inc., in conjunction with Case Western Reserve University is currently developing a family of Nonlinear Adaptive Control algorithms for underactuated mechanical systems based upon this ground breaking research.

Underactuated Systems Control

The pursuit of more capable and versatile systems is driving the need for more and more capable control system design techniques. In particular, control systems are becoming increasing important for bridging gaps left by design tradeoffs. One example of particular interest is the control of a vehicle mounted gun or mortar on a Light Armored Vehicle (LAV). In this application, the transportability of the LAV is of paramount importance and hence, any gun/mount system must be made as light as possible. For the lightweight application envisioned with the LAV, a lighter, and therefore, more flexible structure is necessary to satisfy weight constraints. Unfortunately, the lighter, more flexible structure does not supply a suitable ground for more traditional controllers such as those used to control the main guns of heavier fighting vehicles that possess heavier and more rigid gun mount structures. In order to adequately control gun attitude on the LAV, a control scheme capable of accommodating the system compliance over a large range of operating conditions is needed.



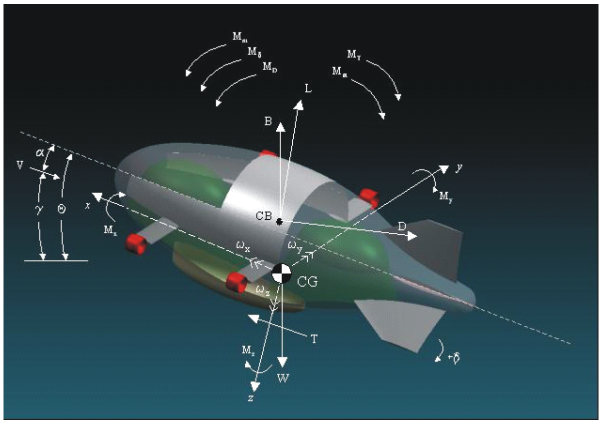
New nonlinear adaptive control techniques can accomodate nonlinear structural flexibility in applications such as light weight gun-mounts for LAV's.

Orbital Research, Inc. (ORI), in conjunction with Case Western Reserve University (CWRU), is developing a suite **nonlinear adaptive controllers** that have a tremendous number of applications. In particular, they are ideally suited for underactuated systems, i.e. for systems that possess more degrees of freedom than control inputs. This type of system occurs frequently in mechanical systems that possess structural flexibility or in the design of fault tolerant controllers to accommodate the loss of actuation. For example, crane booms can have significant flexibility and typically have no actuation designed to control the boom dynamics. Another example is the control of a fighter aircraft, in combat scenarios it may be necessary to control a damaged aircraft that has, for example, lost an engine and has damage to one of its wings. The undamaged control surfaces can be used to compensate for the engine loss, asymmetric flow resulting from wing damage, as well as the loss of control surfaces via higher order coupling effects in the fighter aerodynamics. In both of these cases, it may be impossible to stabilize the systems via any smooth static or dynamic feedback.

Nonlinear Adaptive Control

ORI's approach to nonlinear adaptive control design is markedly different from the majority of systematic design methods for global adaptive control of nonlinear systems with parametric uncertainty. Typical approaches concentrated on adaptive control of feedback linearizable systems with linear parameterization using **smooth feedback**. The majority of the commercially available controllers are smooth or at least C^1 and many inherently nonlinear systems cannot be stabilized by any smooth static or dynamic state feedback. The control design methodology discussed here assumes only continuous (C^0) feedback.

In contrast, the control methodology discussed here focuses on the development of **nonsmooth** but continuous adaptive control schemes for nonlinearly parameterized systems. The approach combines a recently developed extension to the technique of **adding**



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The adaption mechanism provides a means of producing fault tolerant controllers for unmanned air vehicles including high altitude airships.

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power integrator with a new parameter separation technique to produce non-Lipschitz continuous adaptive regulators that achieve global stability with asymptotic state regulation for cases where there do not exist any smooth static or dynamic stabilizers.

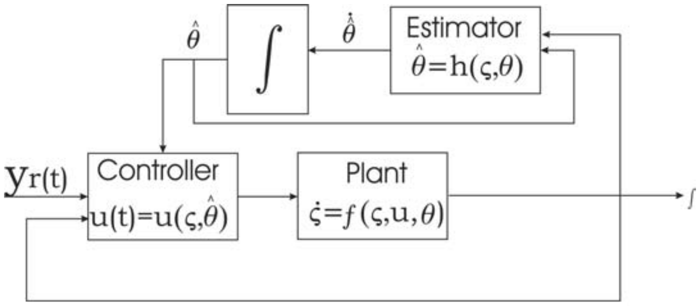
Lin, W., Qian, C., "Adaptive Control of Nonlinearly Parameterized Systems: The Smooth Feedback Case," In IEEE Trans. On Automatic Control, Vol. 47, No. 8, pp. 1249-1266, 2002
Lin, W., Qian, C., "Adaptive Control of Nonlinearly Parameterized Systems: A Nonsmooth Feedback Framework," In IEEE Trans. On Automatic Control, Vol. 47, No. 5, pp. 757-774, 2002

Nonsmooth Adaptive Control

The new results are based upon two new tools for the design of nonlinear control systems, the technique of **adding a power integrator** and a novel **separation principle** that permits the construction of a linear-like parameterized system from a nonlinearly parameterized system.
Qian, C., Lin, W., "Non-Lipschitz continuous stabilizers for nonlinear systems with uncontrollable unstable linearizations," In Syst. Cont. Lett., Vol. 42, No. 3, pp. 33-48, Jan. 1993

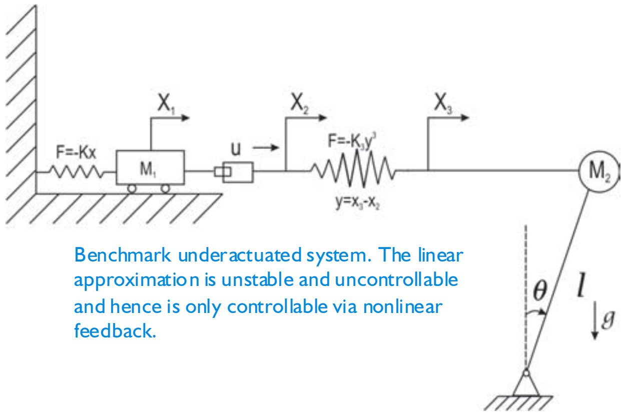
Adding a Power Integrator

A new feedback design tool called *adding a power integrator* is used to solve the problem of global robust stabilization for a significant class of uncertain nonlinear systems that are of a lower triangular form but neither necessarily feedback linearizable (fully or partially) nor affine in the control input. This type of system cannot be dealt with via conventional approaches but under certain conditions, a globally stabilizing smooth state feedback control law can be explicitly constructed by using the technique of adding a power integrator.



Block diagram of nonlinear adaptive controller

The technique of adding a power integrator is a generalization of the technique of **adding a linear integrator**, also known as **backstepping**. The technique of adding a power integrator, however, is not a trivial extension of the integrator backstepping technique because the two tools rely upon very different design philosophies. To wit, traditional *backstepping* techniques focus on "*feedback linearizing*" the system at every step of the recursive design procedure, usually by canceling the nonlinearities using feedback. On the other hand, adding a power integrator focuses on ways to exploit the dominant nonlinearities of the dynamic system in the feedback design. Specifically, this technique relies upon **feedback domination** rather than feedback cancellation. In other words, rather than relying upon nonlinear feedback to cancel nonlinearities, linear and nonlinear control terms are designed so that the effect of the system nonlinearities is negligible. This is crucial as the cancellation of nonlinear terms is analogous to pole-zero cancellation in linear control design and hence can be destabilizing in the presence of parameterization error.
Lin, W., Qian, C., "Adding one power integrator: a tool for global stabilization of high-order lower-triangular systems," In Systems and Control Letters, Vol. 39, pp. 339-351, 2000.



Benchmark underactuated system. The linear approximation is unstable and uncontrollable and hence is only controllable via nonlinear feedback.

A Separation Principle for Nonlinearly Parameterized Systems

The vast majority of results presented in the literature thus far for adaptive control focus on the design of adaptive controllers for nonlinear systems with linear parameterization. That is to say, for systems in which the unknown parameters appear linearly. Recent work at CWRU introduces a novel separation principal that allows a large class of nonlinear systems to be characterized by a **linear-like parameterization**. Specifically, the work shows that every continuous nonlinearly parameterized function $(x \theta)$ can be dominated by two smooth bounding functions $a(x)$, and $b(\theta)$, such that $| (x \theta)| \ a(x)b(\theta)$. Define $\theta \ b(\theta)$ and the *nonlinearly parameterized* function is decomposed as a *linear-like parameterized function* with respect to a new unknown parameter . From this it follows that one can estimate the new parameter $b(\theta)$, instead of θ, and design adaptive controllers directly for the *linear-like parameterized* system. It should be noted here also that the conventional backstepping design cannot be applied to the linear-like parameterized system because it is based upon feedback linearization or cancellation. On the other hand, the technique of adding a power integrator is ideally suited for the design of adaptive controllers for linear-like parameterized systems as it is based upon feedback domination. Due to the nature of a domination design, one needs only knowing of the bounding functions (i.e. $a(x)$, $b(\theta)$), not the precise knowledge of the nonlinearity itself (i.e. $(x \theta)$).
Lin, W., Qian, C., "Adaptive regulation of cascade systems with nonlinear parameterization," In Int. J. of Robust and Nonlinear Control, Vol. 12, pp. 1093-1108, 2001

Adaption

Rather than identify a full set of system parameters via a filtering approach and updating the control laws accordingly as is commonly done, the approach described here must only identify the value of the bounding function,$\theta \ b(\theta)$, and does so via the construction of a **Lyapunov function** and attendant dynamics. By reducing the identification problem to the identification of the value of a single bounding function, a minimal parameterization is which achieved significantly reduces computational overhead. By relying upon a Lyapunov based adaption scheme, the identification can be guaranteed to converge globally and hence the adaptive controller is **Globally Asymptotically Regulating (GAR).**