

Bipedal Locomotion, Robot Gymnastics, and and Robot Air Hockey: A Rapprochement*

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rap·proche·ment (ra'prəsh-män') n. an establishing of friendly relations (Webster's New World Dictionary, 1990).

Abstract

In this paper we discuss control problems in bipedal locomotion, robot gymnastics, and robot air hockey and some interconnections among them. These problems are fundamentally related to the control of redundant and underactuated robots and share some interesting common features, particularly with respect to the application of hybrid and switching control. We discuss the general problem of switching control and relate these concepts to problems of swingup and balance of gymnastic robots and gait control in bipedal locomotion. We also discuss the relationships among hybrid control, impulsive manipulation, visually guided locomotion, and robot air hockey.

1 Introduction

In this paper we discuss some control problems in redundant and underactuated robots from the standpoint of logic-based switching control. Our interest in these problems stems from our recent research projects in the development of gymnastic robots, bipedal robots, visual servoing, and robot air hockey. We identify and discuss some important connections among all of these research areas; indeed, they are all ultimately related to problems of robot locomotion.

Logic-based switching control is useful for this class of systems for several reasons. First is because of the complexity of the nonlinear dynamics; this class of systems contains feedforward nonlinearities, non-minimum phase zero dynamics, unilateral constraints, and other structural properties that often preclude the application of recent design methodologies such as feedback linearization, backstepping, and forwarding.

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Second is because of the nature of disturbances and constraints on states as well as on sensor and actuator performance. For example, studies of human postural control indicate that humans switch among various strategies in response to disturbances and that the degree to which static balance can be maintained depends on force/torque limits. We have designed controllers for redundant robots that switch among different controllers based on sensor and actuator constraints and which achieve better performance than controllers that do not switch (Bishop and Spong, 1998).

Third is because of discontinuous changes in the dynamics of these systems. For example, in bipedal locomotion there are repeated changes in the dynamic structure; in the transition between single support and double support, in gait initiation, gait transitions, as well as the transition between balance and locomotion. Such discontinuous changes in the dynamics naturally suggests the application of switching control.

2 Hybrid and Switching Control

For reasons of space, we give here only a brief overview of the idea of hybrid and switching control. By a hybrid system, \mathcal{H} , (or logic-based switching system) we will mean the following:

$$\mathcal{H} = \{L, U, \Sigma, f, \Gamma\}, \quad \text{where}$$

- $L = \Lambda \times M$ with $\Lambda = \{\lambda_1, \dots, \lambda_k\}$ representing the discrete states
- $M \subset R^n$ is a differentiable manifold representing the continuous states
- $U \subset R^m$ is the admissible continuous control set
- Σ is the admissible discrete control set
- $f : \Lambda \times M \times U \rightarrow TM$ is a vector field assigned to each discrete state
- $\Gamma : L \times \Sigma \rightarrow L$ is a map defining the discrete state transitions

This means essentially that we have a dynamical system

$$\begin{aligned} \dot{x} &= f(\lambda, x, u); \quad \lambda \in \Lambda, \quad x \in M, \quad u \in U \\ &=: f_\lambda(x, u_\lambda) \end{aligned}$$

and a switching logic, defined by Γ , that determines which vector field, f_λ , and control input, u_λ , are active at each moment. The control problem is then not only to determine the continuous control inputs u_λ while f_λ is active, but also the transitions among the vector fields f_λ . These transitions may only be controllable indirectly as in the case of locomotion where they are determined by foot contact with the ground, or they may be directly controlled, as in periodic switching strategies. The switching may result in discontinuities in the vector fields, in the states, or both. One typically assumes only that there are a finite number of switches in each finite time interval. The design of the switching rules and stability analysis is typically based on such tools as *Multiple Lyapunov Functions*, (Branicky, 1994), *Constraint Satisfaction*, (Bishop and Spong, 1998), *Poincare Return Maps*, (Ostrowski and Burdick, 1993) or other methods.

3 Robot Gymnastics

The problem of robot gymnastics (Takashima, 1991; Spong, 1995) is related to the design so-called dextrous robots, such as brachiating robots (Saito, et.al. 1993), and juggling robots (Koditschek 1989), and is of great interest for understanding problems of robot locomotion. For example, both the problem of robot juggling and the problem of running over level ground involve the establishment of stable limit cycle motion. The problems of gait initiation and gait transition, also requires an understanding of static balance and switching between balance and locomotion. These problems are also present in swingup and balance of gymnastic robots.

Results on swingup and balance of gymnastic robots, in particular the Acrobot and Pendubot, are detailed in (Spong, 1995; Spong and Block, 1995) and will not be repeated in detail here. We will only summarize the main ideas in order to show the connections to hybrid control and locomotion. This class of hybrid systems can be represented as a Lagrangian system

$$M(q)\ddot{q} + C(\dot{q}, q)\dot{q} + g(q) = Su_\lambda \tag{1}$$

$$u_\lambda = u_\lambda(q, \dot{q}, t); \quad \lambda \in \{1, \dots, p\} \tag{2}$$

where $M(q)$ is the $n \times n$ inertia matrix, $C(\dot{q}, q)\dot{q}$ represents the Coriolis and centrifugal terms, $g(q)$ represent the gravity terms, and u_λ represents the control input generalized forces. If the input matrix S is invertible, the system is fully actuated, otherwise the system is underactuated and there are unactuated or passive degrees-of-freedom. In the latter case, we can partition the state vector $x = (q, \dot{q})$ as $x = (z, \eta)$, where z and η represent the actuated and passive states, respectively.

For $\lambda = 1$, a control input based on partial feedback linearization can the be designed to produce the cascade system

$$\dot{z} = Az \quad z \in R^{2m} \tag{3}$$

$$\dot{\eta} = w(\eta, z) \quad \eta \in R^{2\ell}; \quad m + \ell = n \tag{4}$$

The design of u_1 is facilitated by the observation that the zero dynamics (the reduced order system obtained from setting $z = 0$) is itself a Lagrangian system and thus has a well defined energy function. Thus energy methods can be used in the design of u_1 by treating z as a fictitious input to (4). For each matrix A , and initial state $z(0)$ the trajectory of (3)-(4) converges to a particular solution of the zero dynamics. For $\lambda > 1$, the control inputs are local controllers designed to balance the robot along an equilibrium manifold. The switching logic, Γ , is based on a Lyapunov analysis to estimate the basins of attraction of the local controllers. The design problem is then to choose u_1 to move the trajectory into the basin of attraction of one of the local controllers and then switch to the local controller. Shown below is a typical example a successful swingup and balance in the case of the Acrobot. See the references at the end for details.

4 Biped Locomotion

To illustrate relevant problems in bipedal locomotion, consider the simplest possible biped, the compass gait, shown in Figure 2, which is equivalent to a double pendulum with point masses

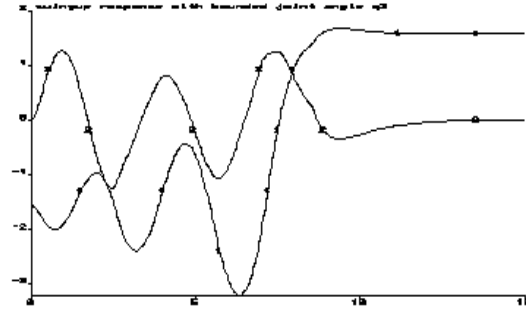


Figure 1: Swingup and Balance of the Acrobot

m_H and m concentrated at the hip and legs. It is well known that systems such as this can "walk" down an incline passively, i.e. without actuators or feedback control of any kind (McGeer, 1990). Assuming a perfectly inelastic collision at foot contact, an instantaneous change in angular velocity results in a loss of kinetic energy while total angular momentum is conserved. A limit cycle results when the velocities after impact equal the initial velocities and the loss of kinetic energy at impact equals the change in potential energy during the step. For a given distribution of masses and leg lengths, and a given ground slope a stable limit cycle may exist as show below. The limit cycles are typical determined from the momentum equations using a numerical search procedure (Goswami, et. al. 1997).

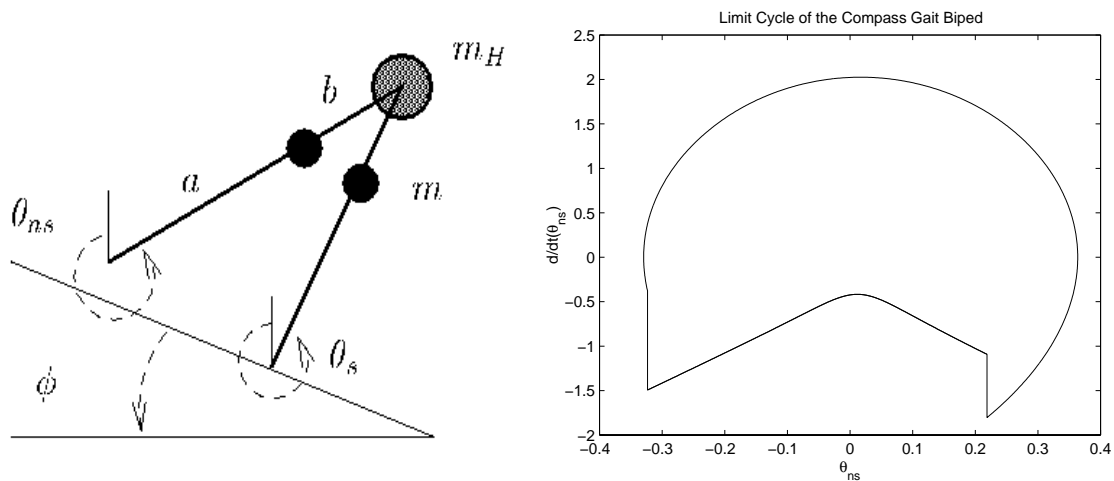


Figure 2: The Compass Gait Biped and Passive Limit Cycle ($\theta_{ns}, \dot{\theta}_{ns}$) for a Three Degree Slope (from Goswami, et.al. (1997).)

The existence of passive gaits in simple bipeds is interesting and may help to explain the efficiency of human locomotion. In (Spong, 1999) we consider the compass gait biped with actuators at the ankle and hip. Since the foot is idealized to a point, we treat the system as though there were a pin joint at the foot/ground interface of the stance leg during the single support phase. As an aside, we remark that using only a hip torque the dynamics are equivalent to the Acrobot (Hauser and Murray, 1990; Spong, 1995), while using only an ankle torque the dynamics are equivalent to the Pendubot (Spong and Block, 1995).

Under the assumption of full actuation, we may, of course, apply any number of tracking controllers that provide global trajectory tracking, such as computed torque. However, a common conjecture in the bipedal locomotion community is that controllers which exploit the "natural dynamics" of the biped will prove to be more energy efficient and will produce more anthropomorphic motion. As in the case of gymnastic robots, the design of such natural controllers may be investigated using energy methods.

For example, it is easy to show for the compass gait that the passive limit cycle of Figure 2 can be made slope invariant by using gravity compensation to shape the potential energy. The idea of shaping the potential energy in robot manipulators goes back to the work of Takegaki and Arimoto (1981) and Koditschek (1989). In this context we only need to know the initial conditions that results in stable walking for one particular slope and we can achieve stable walking on any slope - uphill, downhill, or on level ground. In the case of reduced actuation, i.e., with only an ankle torque or only a hip torque, we can also investigate energy based control laws that exploit the passive limit cycle behavior. The basic idea is to choose the control input to conserve the energy (or an energy-like function) and then to search as before for limit cycle solutions using Poincare analysis. (See (Spong, 1999) for the details.)

In this way stable limit cycle motion of the compass gait robot that is slope invariant may be produced from knowledge of a particular limit cycle for a particular slope. However, the small basin of attraction of the stable limit cycle means that we must, in general, introduce a hybrid/switching control strategy as illustrated by the diagram below in order to achieve robust, global behavior. The "safe" control, e.g. a computed torque type control, is required for global

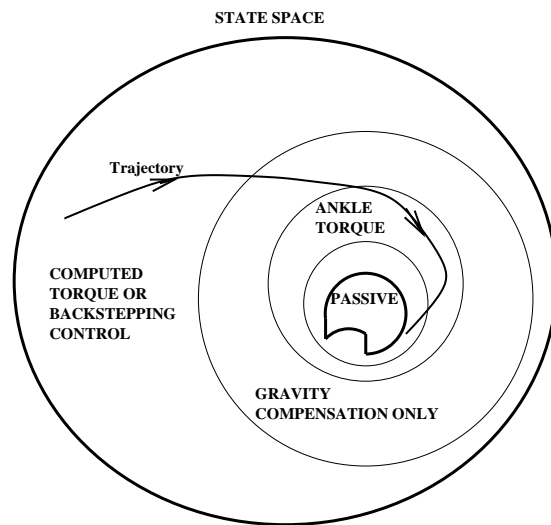


Figure 3: Intuitive Idea behind a Switching Control Strategy to Ensure Global Stability of the Compass Gait

stability. It is designed to bring the system into a neighborhood of the stable limit cycle, where one of the passivity based local controllers can be switched on.

5 Robot Air Hockey

We have built a three-degree-of-freedom air hockey playing robot (Bishop, et. al. 1995) in order to investigate problems of intelligent control and visual servoing. Air hockey falls into the category of impulsive manipulation tasks, which according to Huang, Krotkov, and Mason (1995), are comprised of two phases: a *strike phase* which imparts an instantaneous change of velocity to the object and a *free motion phase* where the object is subject only to environmental forces. Applications such as tapping and batting also fall into this category and have been used successfully for parts manipulation in manufacturing applications.

The connection among impulsive manipulation, air hockey, juggling, and locomotion is the following:

- Bipedal running consists of a ground contact phase, which, in a highly simplified model, can be represented by impulsive forces at the contact foot, and a ballistic or flight phase where there is no contact with the ground. In other words, running is like impulsive manipulation.
- Running over level terrain consists of establishing stable periodic motion of the limbs through the action of these impulsive inputs to the foot. Similarly, juggling consists of inducing periodic trajectories of the objects being juggled through the application of intermittent (possibly impulsive) input forces.
- The analysis of human subjects indicates that visual regulation of step length in running over irregular terrain is achieved primarily by adjusting the vertical impulse imparted to the foot at each step (Warren, et.al., 1986). For this reason robotic air hockey is similar to running over irregular terrain, where vision is used to adjust the impulse imparted to the puck at each "step", i.e., at each mallet/puck interaction.

In the framework of a competitive game, in which the robot seeks to score goals on an opponent while simultaneously protecting its own goal, air hockey requires not only rapid response but also highly accurate estimation of the puck trajectory given a (usually) sparse data set. Using the visually-estimated motion of the puck, the robot must plan and execute trajectories of the circular mallet (attached to the tip of the last link of the manipulator) such that the outgoing puck velocity after impact matches some desired profile.

Our system is shown below in Figure 4. Our hybrid control strategy is based on the fundamental tenet that control should be determined by the reliability of sensor data. This means that the supervisor should choose a conservative control strategy when confidence in the sensor data is low and an aggressive control strategy when confidence in the sensor data is high. Confidence is determined statistically from the sensory data. The supervisory control strategy is shown in Figure 5.

Air hockey is, by nature, time critical and the controller continually operates at or near limits of velocity and torque in order to block and strike the rapidly moving puck. At the same time, our robot has a degree of redundancy which can be used to advantage, such as reconfiguring along the self-motion manifold to maximize manipulability for a strike, etc. Our hybrid control strategy is therefore one of *Constraint Satisfaction* in which separate controllers are designed to satisfy velocity constraints, torque constraints, minimum time requirements, and manipulability requirements and arranged into a hierarchical configuration. Switching occurs based on the reliability of

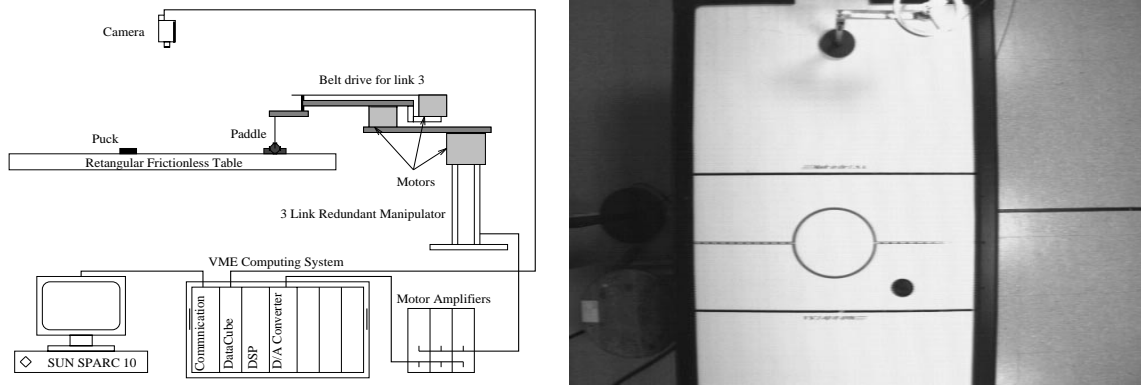


Figure 4: Diagram and overhead view of the experimental setup.

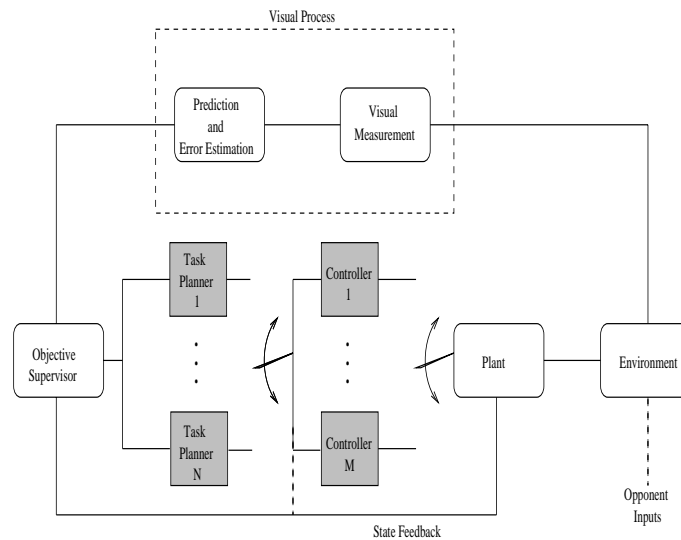


Figure 5: Supervisory Control Architecture

the sensor input data and also to avoid violating any of the constraints in the system. It is shown in (Bishop and Spong, 1998) that such a switching control strategy can perform better than any of the individual controllers working along, and nearly as well as the unconstrained system.

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