

ENERGY INJECTION FOR MECHANICAL SYSTEMS THROUGH THE METHOD  
OF VIRTUAL NONHOLONOMIC CONSTRAINTS

by

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# **Abstract**

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**TODO:** Fill in the abstract

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# Acknowledgements

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# List of Symbols

Symbol	Definition
$\mathbf{n}$	The index set $\{1, \dots, n\}$ of natural numbers up to $n$ .
$\mathbb{R}^n$	Real numbers in $n$ dimensions.
$[\mathbb{R}]_T$	Real numbers modulo $T > 0$ , with $[\mathbb{R}]_\infty = \mathbb{R}$ .
$\mathbb{S}^1$	The unit circle, equivalent to $[\mathbb{R}]_{2\pi}$ .
$\mathcal{Q}$	The configuration manifold of a system.
$C^r(X; Y)$	The space of $r$ -times continuously differentiable functions from $X$ to $Y$ . If $r = \infty$ , the space of smooth functions from $X$ to $Y$ .
$\mathbb{R}^{n \times m}$	The space of real-valued matrices with $n$ rows and $m$ columns.
$I_n$	The $n \times n$ identity matrix.
$\mathbf{0}_{n \times m}$	The $n \times m$ matrix of all zeros.
$M_i$	If $M$ is a vector, the $i$ th element of $M$ . If $M$ is a matrix, the $i$ th column of $M$ .
$M_{i,j}$	The value of row $i$ , column $j$ for the matrix $M$ .
$\dot{x}$	Derivative of $x$ with respect to time $t$ .
$\nabla_v F$	If $F$ is $\mathbb{R}$ -valued, the gradient of $F$ with respect to $v$ . If $F : \mathbb{R}^m \rightarrow \mathbb{R}^{n \times n}$ , the block matrix gradient $(\frac{\partial F}{\partial v_1}, \dots, \frac{\partial F}{\partial v_m}) \in \mathbb{R}^{nm \times n}$ .
$dF_v$	Total differential (Jacobian) of $F$ , equivalent to $(\nabla_v F)^\top$ .
$\text{Hess } F$	If $F : \mathbb{R}^n \rightarrow \mathbb{R}$ , the $n \times n$ Hessian matrix of double derivatives of $F$ . If $F : \mathbb{R}^n \rightarrow \mathbb{R}^k$ , the block matrix $(\text{Hess } F_1, \dots, \text{Hess } F_k) \in \mathbb{R}^{n \times nk}$ .
$\partial_v \partial_w F$	Derivative matrix of $F : \mathbb{R}^n \times \mathbb{R}^m \rightarrow \mathbb{R}$ , with $(i, j)$ element $\frac{\partial^2 F}{\partial v_i \partial w_j}$ .
$\delta_{i,j}$	The Kronecker delta: 1 if $i = j$ and 0 otherwise.
$\otimes$	The matrix kronecker product.
$\ \cdot\ $	The euclidean norm on $\mathbb{R}^n$ .

## TEST CITATIONS:

[1] [2] [3] [4] [5] [6] [7] [8] [9] [10] [11] [12] [13] [14] [15] [16] [17] [18] [19] [20] [21]  
[22] [23] [24] [25] [26] [27] [28] [29] [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] [40]  
[41] [42] [43] [44] [45] [46] [47] [48] [49] [50]



# **Chapter 1**

## **Introduction**

### **1.1 Literature Review**

### **1.2 Statement of Contributions**

### **1.3 Outline of the Thesis**

### **1.4 Notation**

## Chapter 2

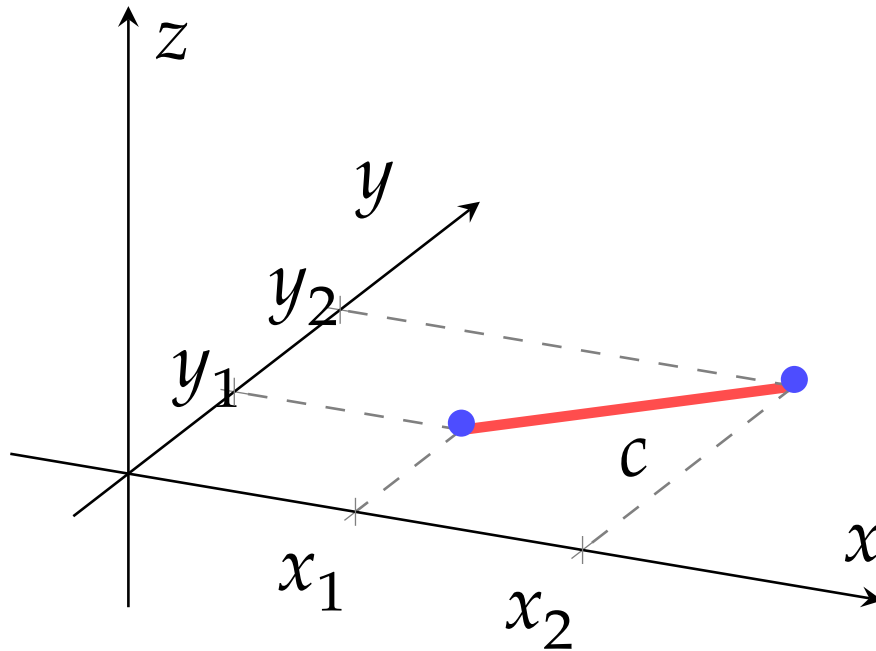
# Development of Virtual Nonholonomic Constraints

### 2.1 Preliminaries on Analytical Mechanics

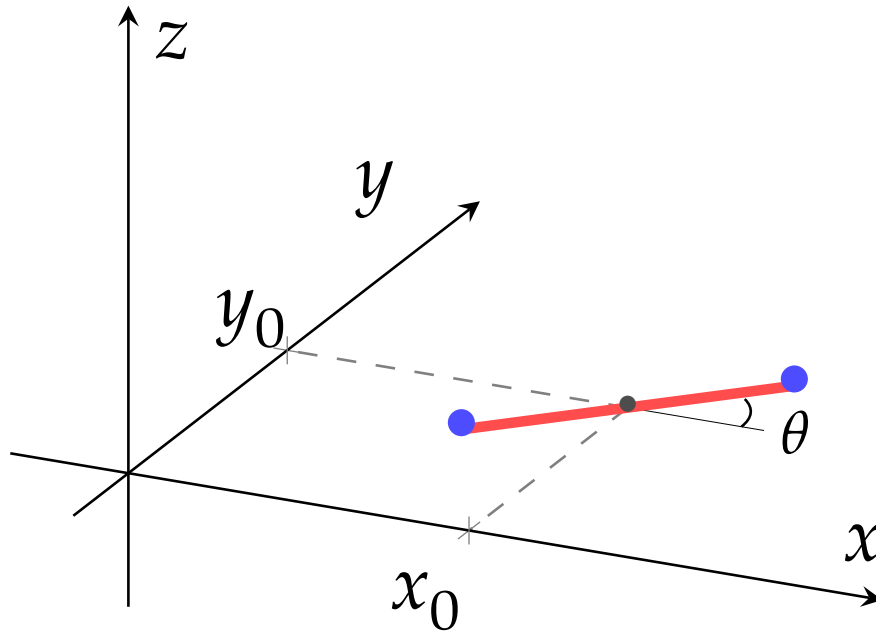
A mechanical system can be represented by  $N$  point masses where each point represents the center of mass of a physical body, along with  $r$  *equations of constraint* (EOC) which model the physical restrictions between these masses. The position of each point mass is described using three cartesian coordinates (one for each spatial axis), so the system as a whole can be described by a vector in  $\mathbb{R}^{3N}$  with  $r$  EOC. The dynamics of the system are computed by deriving the  $3N$  *equations of motion* (EOM) produced by Newton's second law  $F = ma$ . While this technique works for simple systems, it is tedious and becomes impossible to apply to complex mechanical systems where the forces are not explicitly known.

Rather than modeling a mechanical system by cartesian positions and constraints, it is often feasible to represent the position of the system using  $n$  independent scalar-valued variables  $q_1, \dots, q_n$  called *generalized coordinates*, where  $n = 3N - r$  is the number of *degrees of freedom* (DOF) of the system [23]. For instance, Figure 2.1 shows a barbell on a 2D-plane which can rotate freely on that plane. The barbell has  $n = 3$  DOF, so it can be described by three independent generalized coordinates with no equations of constraint.

For the robotic systems of interest in this thesis, we assume that each generalized coordinate  $q_i$  represents either the distance or the angle between two parts of the system. Mathematically, each  $q_i$  takes values in  $[\mathbb{R}]_{T_i}$ , where  $T_i = \infty$  if  $q_i$  represents a length or  $T_i = 2\pi$  if  $q_i$  represents an angle. It is convention to collect the coordinates into a



(A) The Newtonian representation of the barbell requires all six cartesian positions and the corresponding EOC.



(B) One possible set of three generalized coordinates is  $(x_0, y_0, \theta)$ , which represent the position of the center of the bar and the angle of the barbell in the  $xy$ -plane.

FIGURE 2.1: A mechanical system with  $N = 2$  point masses at  $a = (x_1, y_1, z_1)$  and  $b = (x_2, y_2, z_2)$ , separated by a bar of length  $c$ . There are  $r = 3$  EOC given by  $\|a - b\| = c$ ,  $z_1 = 0$ , and  $z_2 = 0$ . This system has  $n = 3$  degrees of freedom.

configuration  $q = (q_1, \dots, q_n) \in \mathcal{Q}$  where the *configuration manifold*  $\mathcal{Q}$  of the system is a so-called *generalized cylinder*

$$\mathcal{Q} = [\mathbb{R}]_{T_1} \times \dots \times [\mathbb{R}]_{T_n}.$$

The derivative  $\dot{q} = (\dot{q}_1, \dots, \dot{q}_n)$  of a configuration is called a *generalized velocity* of the system. For arbitrary systems, the space of allowable velocities depends on the current configuration of the system. However, since  $\mathcal{Q}$  is a generalized cylinder, we find that  $\dot{q} \in \mathbb{R}^n$ . The combined vector  $(q, \dot{q}) \in \mathcal{Q} \times \mathbb{R}^n$  is called a *state* of the system.

The field of analytical mechanics provides a computational method for finding the EOM of a system in generalized coordinates. The two most common analytical methods for modelling robotic systems are *Lagrangian* and *Hamiltonian* mechanics.

### 2.1.1 Lagrangian Mechanics

Lagrangian mechanics uses the kinetic energy  $T(q, \dot{q})$  and potential energy  $P(q)$  of the system to define the Lagrangian  $\mathcal{L} : \mathcal{Q} \times \mathbb{R}^n \rightarrow \mathbb{R}$  defined by (2.1) [23],

$$\mathcal{L}(q, \dot{q}) = T(q, \dot{q}) - P(q). \quad (2.1)$$

When the mechanical system is actuated, the EOM are described by  $n$  second-order ordinary differential equations (ODEs) obtained from the *Euler-Lagrange equations* (2.2) with *generalized input forces*  $\tau \in \mathbb{R}^k$

$$\frac{d}{dt} \left\{ \frac{\partial \mathcal{L}}{\partial \dot{q}_i} \right\} - \frac{\partial \mathcal{L}}{\partial q_i} = B_i^\top(q) \tau. \quad (2.2)$$

The vector  $B_i^\top : \mathcal{Q} \rightarrow \mathbb{R}^{1 \times k}$  describes how the input forces shape the dynamics of  $q_i$ . The matrix  $B : \mathcal{Q} \rightarrow \mathbb{R}^{n \times k}$  with

$$B(q) = \begin{bmatrix} - & B_1^\top(q) & - \\ & \vdots & \\ - & B_n^\top(q) & - \end{bmatrix},$$

is called the *input matrix* for the system. If  $k < n$ , we say the system is *underactuated* with degree of underactuation  $(n - k)$ .

Many actuated mechanical systems have quadratic kinetic energies, so that the Lagrangian can be written explicitly as

$$\mathcal{L}(q, \dot{q}) = \frac{1}{2} \dot{q}^\top D(q) \dot{q} - P(q), \quad (2.3)$$

where the *inertia matrix*  $D : \mathcal{Q} \rightarrow \mathbb{R}^{n \times n}$  is a symmetric, positive definite matrix for all  $q \in \mathcal{Q}$  and the potential function  $P : \mathcal{Q} \rightarrow \mathbb{R}$  is smooth.

### 2.1.2 Hamiltonian Mechanics

Hamiltonian mechanics converts the  $n$  second-order ODEs generated by Lagrangian mechanics into an equivalent set of  $2n$  first-order ODEs.

To do this, we first define the *conjugate of momentum*  $p_i$  to  $q_i$  by

$$p_i(q, \dot{q}) := \frac{\partial \mathcal{L}}{\partial \dot{q}_i}(q, \dot{q}). \quad (2.4)$$

To ease notation, we write  $p = (p_1, \dots, p_n) \in \mathbb{R}^n$  and call  $p$  the *conjugate of momenta* to  $q$ . Note that each  $p_i$  is a linear function of  $\dot{q}$ , and one can typically solve for  $\dot{q}(q, p)$  by inverting all the expressions from (2.4). The combined vector  $(q, p) \in \mathcal{Q} \times \mathbb{R}^n$  is called a *phase* of the system.

The *Hamiltonian* of the system in  $(q, p)$  coordinates is the “Legendre transform” (2.5) of the Lagrangian [24],

$$\mathcal{H}(q, p) := p^\top \dot{q}(q, p) - \mathcal{L}(q, \dot{q}(q, p)). \quad (2.5)$$

The EOM in the Hamiltonian framework are the  $2n$  first-order equations called *Hamilton’s equations*. They are given by

$$\begin{cases} \dot{q} = \nabla_p \mathcal{H} \\ \dot{p} = -\nabla_q \mathcal{H} + B(q)\tau. \end{cases} \quad (2.6)$$

Here,  $B(q) \in \mathbb{R}^{n \times k}$  is the same input matrix used by the Lagrangian framework, with  $\tau \in \mathbb{R}^k$  the same vector of generalized input forces.

If the kinetic energy of the system is quadratic as in (2.3), the conjugate of momenta becomes  $p = D(q)\dot{q}$ . Since  $D(q)$  is symmetric and positive definite, it is invertible at each  $q \in \mathcal{Q}$ . The Legendre transform (2.5) becomes

$$\begin{aligned} \mathcal{H}(q, p) &= p^\top D^{-1}(q)p - \left( \frac{1}{2} p^\top D^{-1}(q)p + P(q) \right) \\ &= \frac{1}{2} p^\top D^{-1}(q)p - P(q). \end{aligned}$$

Finding the derivative of each momentum coordinate yields

$$\dot{p}_i = -\frac{1}{2}p^\top \nabla_{q_i} D^{-1}(q)p - \frac{\partial P}{\partial q_i}(q) + B_i^\top(q)\tau,$$

which can be collected into vector form by using the matrix Kronecker product (see Appendix A). In sum, when the kinetic energy is quadratic the Hamiltonian system reduces to

$$\mathcal{H}(q, p) = \frac{1}{2}p^\top D^{-1}(q)p + P(q), \quad (2.7)$$

$$\begin{cases} \dot{q} = D^{-1}(q)p \\ \dot{p} = -\frac{1}{2}(I_n \otimes p^\top) \nabla_q D^{-1}(q)p - \nabla_q P(q) + B(q)\tau. \end{cases} \quad (2.8)$$

Any set of coordinates  $(q, p)$  which satisfy Hamilton's equations under the Hamiltonian  $\mathcal{H}$  are said to be *canonical coordinates* for the system. A change of coordinates  $(q, p) \rightarrow (Q, P)$  is a *canonical transformation* if  $(Q, P)$  preserve the Hamiltonian structure; that is, if they are canonical coordinates under the Hamiltonian  $\mathcal{H}(q(Q, P), p(Q, P))$ .

Landau and Lifschitz [24] provide a useful result for showing whether a given change of coordinates  $(q, p) \rightarrow (Q, P)$  is a canonical transformation.

**Definition 2.1.** The *Poisson bracket* between the functions  $f(q, p)$  and  $g(q, p)$  is

$$[f, g] := \sum_{i=1}^n \frac{\partial f}{\partial p_i} \frac{\partial g}{\partial q_i} - \frac{\partial f}{\partial q_i} \frac{\partial g}{\partial p_i}. \quad (2.9)$$

**Theorem 2.2.** A change of coordinates  $(q, p) \rightarrow (Q, P)$  is a canonical transformation if and only if

$$\begin{aligned} [Q_i, Q_j] &= 0, \\ [P_i, P_j] &= 0, \\ [P_i, Q_j] &= \delta_{i,j}, \end{aligned}$$

for all  $i, j \in \mathbf{n}$ .

*Proof.* See (45.10) in [24]. □

Later in this chapter we will define a particular change of coordinates. The following Lemma allows us to prove it is a canonical transformation.

**Lemma 2.3.** Let  $\mathcal{H}$  be a Hamiltonian system in canonical coordinates  $(q, p)$ . Let  $A \in \mathbb{R}^{n \times n}$  be an invertible matrix such that  $A^{-1} = A^\top$ . The change of coordinates  $(q, p) \rightarrow (Q = Aq, P = Ap)$  is a canonical transformation.

*Proof.* For any constant matrix  $A$ , the transformation  $(Q = Aq, P = Ap)$  satisfies  $\frac{\partial Q_i}{\partial p_m} = \frac{\partial P_i}{\partial q_m} = 0$  for all  $i, m \in \mathbf{n}$ . Hence,

$$\begin{aligned} [Q_i, Q_j] &= \sum_{m=1}^n \frac{\partial Q_i}{\partial p_m} \frac{\partial Q_j}{\partial q_m} - \frac{\partial Q_i}{\partial q_m} \frac{\partial Q_j}{\partial p_m} = 0, \\ [P_i, P_j] &= \sum_{m=1}^n \frac{\partial P_i}{\partial p_m} \frac{\partial P_j}{\partial q_m} - \frac{\partial P_i}{\partial q_m} \frac{\partial P_j}{\partial p_m} = 0. \end{aligned}$$

Note that  $(A_i)^\top (A^\top)_j = (A_i)^\top (A^{-1})_j = \delta_{i,j}$ . Using this fact we see that the Poisson brackets between  $P_i$  and  $Q_j$  are given by

$$\begin{aligned} [P_i, Q_j] &= \sum_{m=1}^n \frac{\partial P_i}{\partial p_m} \frac{\partial Q_j}{\partial q_m} - \frac{\partial P_i}{\partial q_m} \frac{\partial Q_j}{\partial p_m} \\ &= \sum_{m=1}^n A_{i,m} A_{j,m} - 0 \\ &= \sum_{m=1}^n A_{i,m} (A^\top)_{m,j} \\ &= (A_i)^\top (A^\top)_j \\ &= \delta_{i,j}. \end{aligned}$$

Therefore, by Theorem 2.2, the coordinate change  $(Q = Aq, P = Ap)$  is a canonical transformation.  $\square$

## 2.2 Simply Actuated Hamiltonian Systems

Suppose we are given a Hamiltonian mechanical system (2.7). Because  $\tau$  is transformed by the input matrix  $B(q)$  before entering the EOM, it is not in general clear how any particular input force  $\tau_i$  will affect the dynamics of the system. In this section, we define a new class of Hamiltonian systems where the effect of the input forces is made obvious. This class of systems will form the backbone for the rest of the theory developed in this thesis.

**Definition 2.4.** Let  $\mathcal{H}$  be an  $n$ -DOF Hamiltonian system with  $k \leq n$  actuators. A set of

canonical coordinates  $(q, p)$  for this system are said to be *simply actuated coordinates* if the input matrix  $B(q) \in \mathbb{R}^{n \times k}$  is of the form

$$B(q) = \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix}.$$

The first  $(n - k)$  coordinates, labelled  $q_u$ , are called the *unactuated coordinates*. The remaining  $k$  coordinates, labelled  $q_a$ , are called the *actuated coordinates*. When grouping them together, we will always put them in the order  $(q_u, q_a)$  to fit with the definition. The corresponding  $(p_u, p_a)$  are called the *unactuated* and *actuated momenta*, respectively.

Under the following assumptions on the input matrix, we will show that there is a canonical transformation of (2.7) into simply actuated coordinates.

**Assumption 1.** The input matrix  $B(q) \equiv B \in \mathbb{R}^{n \times k}$  is constant, full rank, and  $k < n$ .

**Assumption 2.** There exists a matrix  $B^\perp \in \mathbb{R}^{(n-k) \times n}$  which is right semi-orthogonal ( $B^\perp (B^\perp)^\top = I_{(n-k)}$ ) and which is a left-annihilator for  $B$ . That is,  $B^\perp B = \mathbf{0}_{(n-k) \times k}$ .

Assumption 2 requires the rows of  $B^\perp$  to be unit vectors that are mutually orthogonal. In the case that  $k = (n - 1)$ , the existence of any left annihilator  $A^0 \in \mathbb{R}^{1 \times n}$  implies the left annihilator  $B^\perp := A^0 / \|A^0\|$  will be a unit vector satisfying Assumption 2.

**Lemma 2.5.** Suppose Assumption 1 holds. Then there exist nonsingular matrices  $V, T \in \mathbb{R}^{k \times k}$  so that the regular feedback transformation

$$\tau = VT\hat{\tau}$$

has a new input matrix  $\hat{B}$  for  $\hat{\tau}$  which is left semi-orthogonal. That is,  $\hat{B}^\top \hat{B} = I_k$ .

*Proof.* Since  $B$  is a constant matrix, it has a singular-value decomposition  $B = U\Sigma V^\top$  where  $U^{-1} = U^\top \in \mathbb{R}^{n \times n}$ ,  $V^{-1} = V^\top \in \mathbb{R}^{k \times k}$ , and  $\Sigma \in \mathbb{R}^{n \times k}$  is defined by

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & \sigma_k \\ - & \mathbf{0}_{(n-k) \times k} & - \end{bmatrix},$$



where  $\sigma_i \neq 0$  because  $B$  is full-rank [49]. Defining  $T \in \mathbb{R}^{k \times k}$  by

$$T = \begin{bmatrix} \frac{1}{\sigma_1} & 0 & \dots & 0 \\ 0 & \frac{1}{\sigma_2} & \dots & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \dots & \frac{1}{\sigma_k} \end{bmatrix},$$

and assigning the regular feedback transformation  $\tau = VT\hat{\tau}$ , we get a new input matrix for  $\hat{\tau} \in \mathbb{R}^k$  given by

$$\hat{B} = BVT = U \begin{bmatrix} I_k \\ \mathbf{0}_{(n-k) \times k} \end{bmatrix},$$

which is still constant and full-rank. In particular,  $\hat{B}^\top \hat{B} = T^\top \Sigma^\top \Sigma T = I_k$ .  $\square$

In light of Lemma 2.5, there is no loss of generality by making the following assumption.

**Assumption 3.** Assume that the input matrix  $B$  is left semi-orthogonal.

Let now  $\mathbf{B} \in \mathbb{R}^{n \times n}$  be the following matrix:

$$\mathbf{B} = \begin{bmatrix} B^\perp \\ B^\top \end{bmatrix}.$$

Since  $B^\perp$  is a left annihilator of  $B$  and both  $B^\perp$  and  $B^\top$  are right semi-orthogonal, it is easy to show that  $\mathbf{B}$  is orthogonal.

*Proof.*

$$\mathbf{B}\mathbf{B}^\top = \begin{bmatrix} B^\perp (B^\perp)^\top & B^\perp B \\ (B^\perp B)^\top & B^\top B \end{bmatrix} = I_n.$$

Hence,  $\mathbf{B}$  is invertible with  $\mathbf{B}^{-1} = \mathbf{B}^\top$ .  $\square$

The following theorem shows that  $\mathbf{B}$  provides a canonical transformation into simply actuated coordinates, so that only the actuated momenta are affected by the input forces.

**Theorem 2.6.** *Under Assumptions 1, 2, and 3, the Hamiltonian system (2.7) has simply actuated*

canonical coordinates  $\{Q = \mathbf{B}q, P = \mathbf{B}p\}$ . The resulting dynamics are given by (2.10),

$$\begin{aligned} \mathcal{H}(Q, P) &= \frac{1}{2}P^\top M^{-1}(Q)P + V(Q), \\ \begin{cases} \dot{Q} = M^{-1}(Q)P \\ \dot{P} = -\frac{1}{2}(I_n \otimes P^\top)\nabla_Q M^{-1}(Q)P - \nabla_Q V(Q) + \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau, \end{cases} \end{aligned} \quad (2.10)$$

where

$$\begin{aligned} M^{-1}(Q) &:= \mathbf{B}D^{-1}(\mathbf{B}^\top Q)\mathbf{B}^\top, \\ V(Q) &:= P(\mathbf{B}^\top Q). \end{aligned}$$

*Proof.* The change of coordinates  $(Q = \mathbf{B}q, P = \mathbf{B}p)$  satisfies Lemma 2.3, making it a canonical transformation. Furthermore, since  $\dot{P} = \mathbf{B}\dot{p}$ , the new input matrix is given by

$$\mathbf{B}\mathbf{B} = \begin{bmatrix} B^\perp B \\ B^\top B \end{bmatrix} = \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix},$$

which means  $(Q = (q_u, q_a), P = (p_u, p_a))$  are simply actuated coordinates for  $\mathcal{H}$  as desired.  $\square$

## 2.3 Virtual Nonholonomic Constraints

Let us imagine a child on a swing who wants to reach the largest height possible. To begin, the child pushes off the ground to imbue the swing with small oscillations. What allows them to increase the amplitude of these oscillations is the appropriate extension and retraction of their feet. If a roboticist were creating a machine to replicate this behaviour, they might design a robot whose legs extend and retract at specific time intervals. At first glance, this technique should work perfectly because the leg motion would synchronize with the swinging frequency, thereby injecting energy as quickly as is physically possible.

Unfortunately, a deeper analysis reveals the flaw with this design. Most children are not counting out the time in their head; rather, they observe their current position and velocity and adjust their legs as required. For example, many children have an adult pushing the swing, or perhaps they are swinging on a windy day. In either case, they adjust their leg motion accordingly when presented with these external

disturbances, without keeping track of time. Hence, the standard control technique of tracking a function of time (known as *trajectory tracking*) does not truly replicate human behaviour. Even if the robot's legs perfectly track a specified trajectory, an external disturbance will desynchronize the leg motion with the swing - thereby stopping the amplitude-increasing effects.

Rather than tracking a trajectory over time, a more human-like behaviour is to force the robot's legs track a function of the swing's state. One recent control method known as *virtual holonomic constraints* (VHCs) uses the actuators to enforce a relation  $h(q) = 0$  of the configuration [19]. This method has provided incredible results in the development of walking robots [27, 28], vehicle motion [30, 31], and has even been used to design a snake-like swimming robot [29].

The downside to VHCs is that they only depend on the configuration of a mechanical system, and not its generalized velocity. For the child on a swing, whether they extend or retract their legs depends on their direction of motion. This inherently requires knowledge of their current velocity, which precludes the usage of VHCs. A few authors have attempted to extend the theory of VHCs to enforce relations  $h(q, \dot{q}) = 0$  of the full state to account for this drawback. Since these relations use actuators to restrict both the configuration and velocity of a system, they are called virtual *nonholonomic* constraints. This idea has been used for human-robot interaction [32–34], error-reduction on time-delayed systems [35], and has shown marked improvements to the field of bipedal locomotion [9, 36, 38]. Most interestingly, this nonholonomic approach is more robust than standard VHCs when applied to bipedal robotics [37]. In particular, virtual nonholonomic constraints may be capable of injecting and dissipating energy from a system in a robust manner, all while producing realistic biological motion. This is what we aim to prove in this thesis.

Unlike the theory of VHCs, there does not appear to be a standard definition of virtual nonholonomic constraints: all the applications listed above use their own definitions, which makes it difficult to compare and generalize their work.

This section will provide a standard characterization of virtual nonholonomic constraints using Hamiltonian mechanics. The goal is to provide a consistent, rigorous foundation for designing constraints on a general class of systems.

**Definition 2.7.** A *virtual nonholonomic constraint* (VNHC) of order  $k$  is a relation  $h(q, p) = 0$  where  $h : \mathcal{Q} \times \mathbb{R}^n \rightarrow \mathbb{R}^k$  is  $C^2$ ,  $\text{rank}([dh_q, dh_p]) = k$  for all  $(q, p) \in h^{-1}(0)$ , and there exists a feedback controller  $\tau(q, p)$  stabilizing the *constraint manifold*

$$\Gamma = \{(q, p) \mid h(q, p) = 0, dh_q \dot{q} + dh_p \dot{p} = 0\}.$$

From the definition of VNHCs, one finds that the constraint manifold  $\Gamma$  is a  $2(n - k)$ -dimensional surface inside  $\mathcal{Q} \times \mathbb{R}^n$ . The next obvious question is the following: when does a feedback controller stabilizing  $\Gamma$  exist?

One approach to answering this question is to define the error term  $e = h(q, p)$ . If there exists some controller  $\tau(q, p)$  driving  $e \rightarrow 0$  and  $\dot{e} \rightarrow 0$ , then the same  $\tau$  will necessarily stabilize  $\Gamma$ .

If  $\tau$  first appears after  $r_i > 0$  derivatives of  $e_i$ , then  $e_i$  is said to have *relative degree*  $r_i$ . Collecting the  $e_i$  together, we say that  $e$  is of relative degree  $\{r_1, \dots, r_k\}$ . With no further structure on  $h(q, p)$ , the control input  $\tau$  usually appears after one derivative of  $e$ ; unfortunately, if any  $e_i$  has relative degree  $r_i = 1$  we may not be able to stabilize  $\Gamma$ . We could guarantee  $h(q, p) \rightarrow 0$ , but we could not in general guarantee  $\dot{h}(q, p) \rightarrow 0$ .

Requiring  $e$  to have relative degree  $\{2, \dots, 2\}$  is much more useful, since it allows us to easily solve for a controller stabilizing  $\Gamma$ . This kind of relative degree requirement is already common in the VHC literature. Taking advantage of that precedent, we define a special type of VNHC that satisfies this property.

**Definition 2.8.** A VNHC  $h(q, p) = 0$  of order  $k$  is *regular* if the output  $e = h(q, p)$  is of relative degree  $\{2, 2, \dots, 2\}$  everywhere on the constraint manifold  $\Gamma$ .

The authors of [9, 36, 37] observed that a relation which uses only the unactuated conjugate of momentum cannot have  $\tau$  appearing after only one derivative. Of course, they performed their research in Lagrangian form; we will be using the Hamiltonian formulation from Chapter 2.2. As a reminder, our system is described in  $(q, p)$  coordinates with  $q = (q_u, q_a)$  and  $p = (p_u, p_a)$  and has the dynamics

$$\mathcal{H}(q, p) = p^\top M^{-1}(q)p + V(q), \quad (2.11)$$

$$\begin{cases} \dot{q} = M^{-1}p \\ \dot{p} = -\frac{1}{2}(I_n \otimes p^\top) \nabla_q M^{-1}(q)p - \nabla_q V(q) + \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau. \end{cases} \quad (2.12)$$

*Notation.* We will write  $q_u \in \mathcal{Q}_u, q_a \in \mathcal{Q}_a$  where  $\mathcal{Q}_u \times \mathcal{Q}_a = \mathcal{Q}$ . We also write  $p_u \in \mathcal{P}_u := \mathbb{R}^{n-k}$  and  $p_a \in \mathcal{P}_a := \mathbb{R}^k$ , so that  $p \in \mathcal{P} := \mathcal{P}_u \times \mathcal{P}_a = \mathbb{R}^n$ . In this manner, the phase space of our system can be written as  $\mathcal{Q} \times \mathcal{P}$ .

**Theorem 2.9.** A VNHC  $h(q, p) = 0$  of order  $k$  is regular if and only if  $dh_{p_a} = 0$  and

$$\text{rank} \left( \left( dh_q M^{-1}(q) - dh_{p_u} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q) \right) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \right) = k,$$

everywhere on the constraint manifold  $\Gamma$ .

*Proof.* Let  $e = h(q, p) \in \mathbb{R}^k$ . Then

$$\begin{aligned} \dot{e} &= dh_q \dot{q} + dh_p \dot{p} \\ &= dh_q M^{-1}(q)p + \\ &\quad \begin{bmatrix} dh_{p_u} & dh_{p_a} \end{bmatrix} \left( -\frac{1}{2} \begin{bmatrix} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p \\ (I_k \otimes p^\top) \nabla_{q_a} M^{-1}(q)p \end{bmatrix} - \begin{bmatrix} \nabla_{q_u} V(q) \\ \nabla_{q_a} V(q) \end{bmatrix} + \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau \right). \end{aligned}$$

If  $dh_{p_a} \neq \mathbf{0}_{k \times k}$  for some  $(q, p)$  on  $\Gamma$ , then  $\tau$  appears in  $\dot{e}$  and the VNHC is not of relative degree  $\{2, 2, \dots, 2\}$ . Hence, we must have that  $dh_{p_a} = \mathbf{0}_{k \times k}$ . Proceeding with this assumption, we now find that  $h : \mathcal{Q} \times \mathcal{P}_u \rightarrow \mathbb{R}^k$ , which means that

$$\dot{e} = dh_q M^{-1}(q)p - dh_{p_u} \left( \frac{1}{2} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p + \nabla_{q_u} V(q) \right).$$

Taking one further derivative provides

$$\begin{aligned} \ddot{e} &= \left( \frac{d}{dt} dh_q \right) M^{-1}(q)p + dh_q \left( \sum_{i=1}^n \frac{\partial M^{-1}}{\partial q_i}(q) \dot{q}_i \right) p + dh_q M^{-1}(q) \dot{p} - \\ &\quad \left( \frac{d}{dt} dh_{p_u} \right) \left( \frac{1}{2} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p + \nabla_{q_u} V(q) \right) - \\ &\quad dh_{p_u} \left( \frac{1}{2} \frac{d}{dt} \left( (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p \right) + \left( \frac{d}{dt} \nabla_{q_u} V(q) \right) \right). \end{aligned}$$

Most of these terms do not involve  $\dot{p}$  and hence do not contain  $\tau$ , so we shorten this to

$$\ddot{e} = (*) - dh_{p_u} \left( \frac{1}{2} \frac{d}{dt} \left( (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p \right) \right) + dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau.$$

Observe that the  $i^{\text{th}}$  row of  $\frac{1}{2} \frac{d}{dt} \left( (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p \right)$  is given by

$$\frac{1}{2} \frac{d}{dt} \left( p^\top \frac{\partial M^{-1}}{\partial q_{u_i}}(q)p \right) = p^\top \frac{\partial M^{-1}}{\partial q_{u_i}}(q) \dot{p} + \frac{1}{2} p^\top \left( \sum_{j=1}^n \frac{\partial^2 M^{-1}}{\partial q_{u_i} \partial q_j} \dot{q}_j \right) p.$$

Highlighting only the term containing  $\tau$ , we get the vector form

$$\frac{1}{2} \frac{d}{dt} \left( (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q)p \right) = (*) + (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau.$$

Plugging this into  $\ddot{e}$  reveals that

$$\ddot{e} = (\star) + \left( dh_q M^{-1}(q) - dh_{p_u} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q) \right) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \tau,$$

where  $(\star)$  is a continuous function of  $q$  and  $p$ . For shorthand, we'll write

$$\ddot{e} = E(q, p) + H(q, p) \tau,$$

where  $E$  and  $H$  are defined appropriately. From the definition of regularity, the VNHC  $h$  is regular when  $e$  is of relative degree  $\{2, \dots, 2\}$ , which is true if and only if the matrix premultiplying  $\tau$  is nonsingular, and hence that  $H$  is invertible. This proves the theorem.  $\square$

Using the expression  $\ddot{e} = E(q, p) + H(q, p) \tau$  from the proof of Theorem 2.9, a regular VNHC of order  $k$  can be stabilized by the output-linearizing phase-feedback controller

$$\tau(q, p) = -H^{-1}(q, p) \left( E(q, p) + k_p e + k_d \dot{e} \right), \quad (2.13)$$

where  $k_p, k_d \in \mathbb{R}_{>0}$  are control parameters which can be tuned on the resulting linear system  $\ddot{e} = -k_p e - k_d \dot{e}$ .

Note that one generally cannot measure conjugate of momenta directly, as sensors on mechanical systems will only measure the state  $(q, \dot{q})$ . To implement this controller in practice, one must compute  $p = M(q)\dot{q}$  at every iteration. In other words, this controller requires knowledge of the full state of the system.

Now that we have found a controller to enforce a regular VNHC of order  $k$ , we would like to determine the dynamics on the constraint manifold  $\Gamma$ . Intuitively, these dynamics should be parameterized by  $(q_u, p_u)$  since  $q_a$  is a function of these as specified by  $h(q, p_u) = 0$ . Unfortunately,  $\dot{q}_u$  depends on  $p_a$ , and for general systems one cannot solve explicitly for  $p_a$  in terms of  $(q_u, p_u)$ . This is because the  $\dot{p}$  dynamics contains the coupling term  $(I_n \otimes p^\top) \nabla_{q_u} M(q) p$ .

We now introduce an assumption so we can solve explicitly for the constrained dynamics.

**Assumption 4.** The Hamiltonian system has an inertia matrix that does not depend on the unactuated coordinates:

$$\nabla_{q_u} M(q) = \mathbf{0}_{n(n-k) \times n}.$$

**Theorem 2.10.** *Let  $\mathcal{H}$  be a mechanical system in simply actuated coordinates satisfying Assumption 4. Let  $h(q, p_u) = 0$  be a regular VNHC of order  $k$  with constraint manifold  $\Gamma$ . Suppose that on  $\Gamma$  one can solve for  $q_a$  as a function of  $(q_u, p_u)$ . Then the constrained dynamics are given by*

$$\begin{aligned} \dot{q}_u &= \begin{bmatrix} I_{(n-k)} & \mathbf{0}_{(n-k) \times k} \end{bmatrix} M^{-1}(q) p \\ \dot{p}_u &= -\nabla_{q_u} V(q) \end{aligned} \quad \left| \begin{array}{l} h(q, p_u) = 0 \\ p_a = g(q_u, p_u) \end{array} \right. , \quad (2.14)$$

where

$$g(q_u, p_u) := \left( dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \right)^{-1} \left( dh_{p_u} \nabla_{q_u} V(q) - dh_q M^{-1}(q) \begin{bmatrix} I_{n-k} \\ \mathbf{0}_{k \times (n-k)} \end{bmatrix} p_u \right) \Big|_{h(q, p_u)=0}. \quad (2.15)$$

*Proof.* Setting  $e = h(q, p_u)$  and using the fact that  $\nabla_{q_u} M^{-1}(q) = 0$ , we find that

$$\dot{e} = dh_q M^{-1}(q) p - dh_{p_u} \nabla_{q_u} V(q).$$

Observe that

$$\begin{aligned} dh_q M^{-1}(q) p &= dh_q M^{-1}(q) \begin{bmatrix} p_u \\ p_a \end{bmatrix} \\ &= dh_q M^{-1}(q) \begin{bmatrix} I_{n-k} & \mathbf{0}_{(n-k) \times k} \\ \mathbf{0}_{k \times (n-k)} & I_k \end{bmatrix} \begin{bmatrix} p_u \\ p_a \end{bmatrix} \\ &= dh_q M^{-1}(q) \begin{bmatrix} I_{n-k} \\ \mathbf{0}_{k \times (n-k)} \end{bmatrix} p_u + dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} p_a. \end{aligned}$$

On the constraint manifold, we have  $e = \dot{e} = 0$ , which means

$$dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} p_a = dh_{p_u} \nabla_{q_u} V(q) - dh_q M^{-1}(q) \begin{bmatrix} I_{n-k} \\ \mathbf{0}_{k \times (n-k)} \end{bmatrix} p_u.$$

Since  $h$  is regular and  $\nabla_{q_u} M^{-1}(q) = 0$ , we have that

$$\text{rank} \left( dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \right) = k.$$

Solving for  $p_a$  gives

$$p_a(q, p_u) = \left( dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix} \right)^{-1} \left( dh_{p_u} \nabla_{q_u} V(q) - dh_q M^{-1}(q) \begin{bmatrix} I_{n-k} \\ \mathbf{0}_{k \times (n-k)} \end{bmatrix} p_u \right).$$

This yields a function  $p_a(q, p_u)$ . However, on  $\Gamma$  we have  $h(q, p_u) = 0$  and can solve for  $q_a$  in terms of  $(q_u, p_u)$ ; hence, we can solve for  $p_a = g(q_u, p_u)$ . Since  $q_a$  and  $p_a$  can be computed directly from  $(q_u, p_u)$ , the dynamics on  $\Gamma$  are parameterized only by  $(\dot{q}_u, \dot{p}_u)$ .  $\square$

Theorem 2.10 shows that, for a particular class of systems and constraints, the dynamics on  $\Gamma$  are entirely described by the  $2(n - k)$  unactuated coordinates. This is true regardless of the number of degrees of freedom of the system.

The following corollary applies Theorem 2.10 to systems with only one unactuated coordinate.

**Corollary.** Suppose  $\mathcal{H}$  is a mechanical system in simply actuated coordinates satisfying Assumption 4 which has degree of underactuation one. Let  $h(q, p_u) = 0$  be a regular VNHC of order  $(n - 1)$  of the form  $h(q, p_u) = q_a - f(q_u, p_u)$ , where  $f$  is a suitably defined  $C^2$  function. Then  $dh_q = [-\partial_{q_u} f \quad I_{(n-1)}]$ . Defining  $e_1 := (1, 0, \dots, 0) \in \mathbb{R}^n$ , the actuated momentum is

$$p_a = - \left( dh_q M^{-1}(q) \begin{bmatrix} \mathbf{0}_{1 \times (n-1)} \\ I_{(n-1)} \end{bmatrix} \right)^{-1} \left( \partial_{p_u} f \partial_{q_u} V + dh_q M^{-1}(q) e_1 p_u \right) \Big|_{q_a = f(q_u, p_u)}. \quad (2.16)$$

Since  $q_u \in [\mathbb{R}]_{T_u}$  for some  $T_u \in ]0, \infty]$  and  $p_u \in \mathbb{R}$ , the orbit  $(q_u(t), p_u(t))$  traces out a curve on the 2D-plane  $[\mathbb{R}]_{T_u} \times \mathbb{R}$  which we call the  $(q, p)$ -plane.

## 2.4 Summary of Results

In this chapter, we developed the framework of virtual nonholonomic constraints for underactuated Hamiltonian mechanical systems. We made the following assumptions:

1. The input matrix  $B(q) \equiv B \in \mathbb{R}^{n \times k}$  is constant and full rank.
2. The input matrix has a left-annihilator  $B^\perp \in \mathbb{R}^{(n-k) \times n}$ .
3. The annihilator matrix  $B^\perp$  is right semi-orthogonal.

These assumptions allowed us to define a canonical change of coordinates into the simply actuated coordinates  $(q, p) \in \mathcal{Q} \times \mathcal{P}$ , where  $q = (q_u, q_a)$  and  $p = (p_u, p_a)$ .



We defined a virtual nonholonomic constraint as a function  $h \in C^2(\mathcal{Q} \times \mathcal{P}; \mathbb{R}^k)$  which has no singular points on its constraint manifold

$$\Gamma = \{(q, p) \mid h(q, p) = 0, dh_q \dot{q} + dh_p \dot{p} = 0\}.$$

We then showed that a VNHC  $h : \mathcal{Q} \times \mathcal{P}_u \rightarrow \mathbb{R}^k$  is regular if and only if the square matrix

$$\left( dh_q M^{-1}(q) - dh_{p_u} (I_{n-k} \otimes p^\top) \nabla_{q_u} M^{-1}(q) \right) \begin{bmatrix} \mathbf{0}_{(n-k) \times k} \\ I_k \end{bmatrix}$$

is invertible on  $\Gamma$ .

To find the explicit equations for constrained dynamics of a regular VNHC, we made the following assumptions:

- The inertia matrix satisfies  $\nabla_{q_u} M(q) = \mathbf{0}_{n(n-k) \times n}$ .
- On  $\Gamma$ , one can solve for  $q_a$  as a function of  $(q_u, p_u)$ .

If these assumptions hold, one can solve for  $p_a = g(q_u, p_u)$  on  $\Gamma$ . The constrained dynamics are then given by  $(\dot{q}_u, \dot{p}_u)$  subject to  $h(q, p_u) = 0$  and  $p_a = g(q_u, p_u)$ .

Finally, we saw the benefit of using VNHCs is that they reduce the dimensionality of the system from  $2n$  equations of motion to  $2(n - k)$  equations, which significantly reduces the complexity of analyzing large systems. In particular, if the system has degree of underactuation one, the dynamics reduce to a 2D system on the “ $(q, p)$ -plane”  $[\mathbb{R}]_T \times \mathbb{R}$ .

## Chapter 3

# Application of VNHCS: The Variable Length Pendulum

### 3.1 Motivation

The variable length pendulum (VLP) is a classical underactuated dynamical system which is often used to model the motion of a person on a swing [8, 16]. The VLP also represents the motion of the load at the end of a crane, the (simplified) motion of a gymnast on a bar [15], and the tuned-mass-damper systems which stabilize skyscrapers [41].

The motion of the VLP has been well studied (see for instance [39]), and many control mechanisms exist to stabilize trajectories of the system. While many of these controllers are time-dependent, Xin and Liu [20] offer a time-independent technique to inject energy into the VLP. They design a controller through a technique called *energy shaping* and prove that it stabilizes any desired energy level set. However, their control input depends on a pre-specified target energy and requires knowledge of the current total energy of the VLP. This makes their energy injection mechanism “ad-hoc” in the sense that it is tailored very specifically to the VLP, and is not generalizable to a larger methodology.

It may be better to base the control design on natural biological behaviour. In this chapter we will make use of the general VNHC framework developed in Chapter 2 to add and remove energy from the VLP in a time-independent manner. We’ll show that, unlike energy shaping, VNHCS can be used to stabilize energy levels while maintaining the structured motion of a human on a swing.

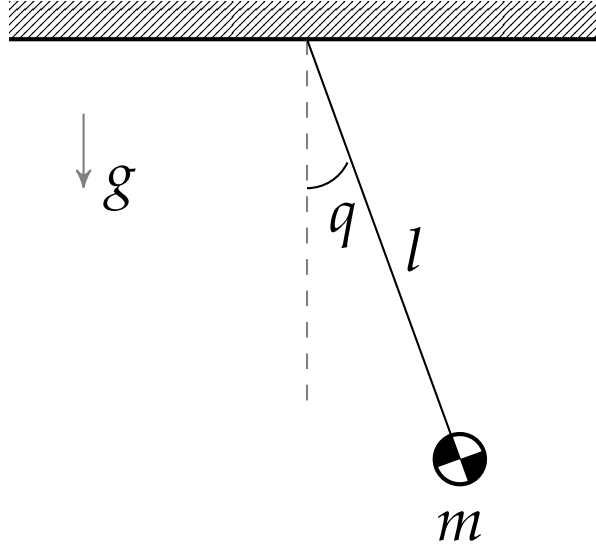


FIGURE 3.1: The variable length pendulum is a mass attached to the tip of a massless rod which can change length.

## 3.2 Dynamics of the Variable Length Pendulum

We will model the VLP as a point mass  $m$  connected to a fixed pivot by a massless rod of varying length  $l$  with angle  $q \in \mathbb{S}^1$  from the vertical, as in Figure 3.1. We will ignore any damping and frictional forces in this model. In a realistic VLP, the rod length  $l$  varies between some minimum length  $\underline{l} \geq 0$  and some maximum length  $\bar{l} > \underline{l}$ . The configuration of the VLP is the vector  $\mathbf{q} := (q, l) \in \mathbb{S}^1 \times [\underline{l}, \bar{l}]$ .

Using this configuration, we will compute the Hamiltonian dynamics of the system. The cartesian position of the mass at the tip of the pendulum is given by  $x = (l \sin(q), -l \cos(q))$ , while its velocity is  $\dot{x} = (\dot{l} \sin(q) + l \cos(q) \dot{q}, -\dot{l} \cos(q) + l \sin(q) \dot{q})$ . Computing the kinetic energy  $T$  yields

$$T(\mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{2} m \|\dot{x}\|^2 = \frac{1}{2} m (\dot{l}^2 + l^2 \dot{q}^2).$$

The potential energy  $P$  with respect to the pivot (under a gravitational acceleration  $g$ ) is

$$P(\mathbf{q}) = -mgl \cos(q).$$

Collecting the kinetic energy into a quadratic form, we get the Lagrangian

$$\mathcal{L}(\mathbf{q}, \dot{\mathbf{q}}) = \frac{1}{2} \dot{\mathbf{q}}^T D(\mathbf{q}) \dot{\mathbf{q}} - P(\mathbf{q}) = \frac{1}{2} \begin{bmatrix} \dot{q} & \dot{l} \end{bmatrix} \begin{bmatrix} ml^2 & 0 \\ 0 & m \end{bmatrix} \begin{bmatrix} \dot{q} \\ \dot{l} \end{bmatrix} + mgl \cos(q).$$

Computing the conjugate of momenta to  $\mathbf{q}$ , we get

$$\mathbf{p} := \begin{bmatrix} p \\ p_l \end{bmatrix} = \begin{bmatrix} ml^2 \dot{q} \\ ml \end{bmatrix}.$$

Performing the Legendre transform on  $\mathcal{L}$  and setting  $M(\mathbf{q}) := D(\mathbf{q})$ ,  $V(\mathbf{q}) := P(\mathbf{q})$ , we get the Hamiltonian (2.11) whose dynamics (2.12) resolve to

$$\begin{aligned} \mathcal{H} &= \frac{1}{2} \begin{bmatrix} p & p_l \end{bmatrix} \begin{bmatrix} \frac{1}{ml^2} & 0 \\ 0 & \frac{1}{m} \end{bmatrix} \begin{bmatrix} p \\ p_l \end{bmatrix} - mgl \cos(q), \\ \begin{cases} \dot{q} &= \frac{p}{ml^2} \\ \dot{l} &= \frac{p_l}{m} \\ \dot{p} &= -mgl \sin(q) \\ \dot{p}_l &= \frac{p^2}{ml^3} + mg \cos(q) + \tau. \end{cases} \end{aligned} \quad (3.1)$$

The control input is a force  $\tau \in \mathbb{R}$  affecting the dynamics of  $p_l$ , acting colinearly with the rod. We assume the force does not affect the dynamics of  $p$  in any way - that is, the control input cannot enact any lateral force on the pendulum. This makes the VLP into an underactuated mechanical system with degree of underactuation one. It is also a useful assumption because it means  $(\mathbf{q}, \mathbf{p})$  are simply actuated coordinates, which allows us to apply the theory of VNHCS we developed in Chapter 2.

Let us define the VNHC  $l = L(q, p)$ , by which we mean we are actually defining the VNHC  $h(\mathbf{q}, \mathbf{p}) = l - L(q, p) = 0$  of order 1. The VLP satisfies  $\nabla_{\mathbf{q}} M^{-1}(\mathbf{q}) = \mathbf{0}_{2 \times 2}$ . By Theorem 2.9,  $h(\mathbf{q}, \mathbf{p})$  is a regular VNHC whenever  $L(q, p)$  is  $C^2$  because

$$dh_{\mathbf{q}} M^{-1}(\mathbf{q}) B = \begin{bmatrix} -\frac{\partial L}{\partial q} & 1 \end{bmatrix} \begin{bmatrix} \frac{1}{ml^2} & 0 \\ 0 & \frac{1}{m} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \frac{1}{m}$$

is always full rank. The constraint manifold is  $\Gamma = \mathbb{S}^1 \times \mathbb{R}$ , which is parameterized by the unactuated phase  $(q, p)$ . The constrained dynamics are Hamiltonian, and Theorem 2.10 tells us they are described entirely by  $(\dot{q}, \dot{p})$  with  $l$  replaced by  $L(q, p)$ :

$$\begin{aligned} \mathcal{H}(q, p) &= \frac{1}{2} \frac{p^2}{mL^2} - \frac{1}{2} \dot{L}^2 - mgL \cos(q), \\ \begin{cases} \dot{q} &= \frac{p}{mL^2} \\ \dot{p} &= -mgL \sin(q). \end{cases} \end{aligned} \quad (3.2)$$

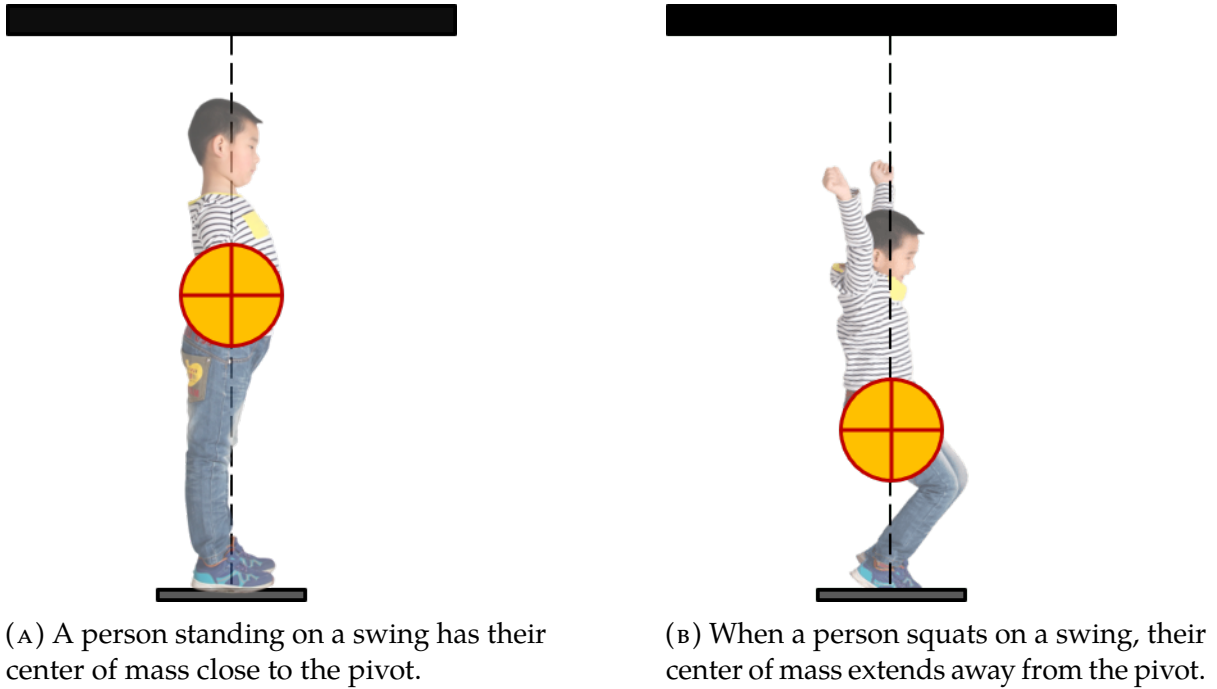


FIGURE 3.2: The VLP representation of a person on a standing swing.

Note that we suppress the function notation of  $L(q, p)$  and  $\dot{L}(q, p)$  for clarity.

The total mechanical energy of the system restricted to the constraint manifold is given by (3.3), where  $L(q, p)$  and  $\dot{L}(q, p)$  are known.

$$E(q, p) = \frac{1}{2} \frac{p^2}{mL^2} + \frac{1}{2} \dot{L}^2 - mgL \cos(q) \quad (3.3)$$

In the rest of this chapter, we will derive a  $C^2$  function  $L(q, p)$  based on natural human motion. This function will produce constrained dynamics that inject energy into the VLP.

### 3.3 The VLP Constraint

To motivate why a VNHCS could inject energy into the VLP in a human-like manner, we will examine a person standing on a swing. As can be seen in Figure 3.2, a person's center of mass moves closer to the swing's pivot when they stand, and moves away from the pivot when they squat. This is equivalent to the VLP model from Figure 3.1, where standing and squatting correspond to shortening and lengthening the pendulum respectively.

The action of regulating pendulum length to inject energy into the VLP is known as

“pumping”. Piccoli and Kulkarni [16] asked whether the pumping strategy performed by children is time-optimal, assuming the children could squat or stand instantaneously. Indeed, they discovered that children increase the height of their swing as fast as is physically possible.

A child’s optimal pumping strategy is the following: they stand at the lowest point of the swing, and squat at the highest point. Looking at the VLP representation, the pendulum shortens at the bottom of the swing, and lengthens at the top. For an intuitive explanation, conservation of angular momentum indicates that shortening the pendulum at the bottom forces the mass to gain speed to compensate for the reduced length [8]. Energy is not conserved in this process, so the pendulum gains kinetic energy and reaches a higher point at the peak of its swing. Lengthening the pendulum when it reaches this peak means gravity imparts a larger angular momentum to the mass by the time it reaches the bottom of its swing, which in turn is converted to a higher velocity when the pendulum is shortened. By alternating these processes, the pendulum experiences an average net gain in rotational energy.

Notice that the child’s pumping strategy requires knowledge of when the system is at the “bottom” or “top” of the swing. Since being at the bottom is equivalent to having angle  $q = 0$  and being at the top is equivalent to having momentum  $p = 0$ , a controller based on this strategy will necessarily involve the full unactuated phase  $(q, p)$ . This is why we must use VNHCS instead of other methods (such as VHCs) to perform this maneuver.

The time-optimal controller from [16] is, in our notation,

$$L^*(q, p) := -\operatorname{sgn}(qp),$$

which is a piecewise-continuous controller that varies between  $\pm 1$ . We could set our constraint to be  $l = L^*(q, p)$ , but this is not a VNHC because it is not  $C^2$ . Additionally, it would force us to assume that  $l \in \{-1, 0, 1\}$  and that one can switch  $l$  instantaneously. Since we need to enforce the constraint using the physical input  $\tau$  (which would ideally emulate realistic human motion), we cannot use  $L^*$  as our VNHC. We will instead find an alternate representation of  $L^*$  which can be converted into a VNHC, and which allows  $l \in [L, \bar{L}]$ .

Figure 3.3a displays  $L^*(q, p)$  on the  $(q, p)$ -plane. Note that the length remains constant inside each quadrant and changes only when it crosses one of the axes. Using this fact, we can redefine the time-optimal pumping strategy as a function of  $\theta := \arctan_2(p, q)$ . Abusing notation, we denote this by  $L^*(\theta)$ , which is defined in (3.4). Figure 3.3b shows

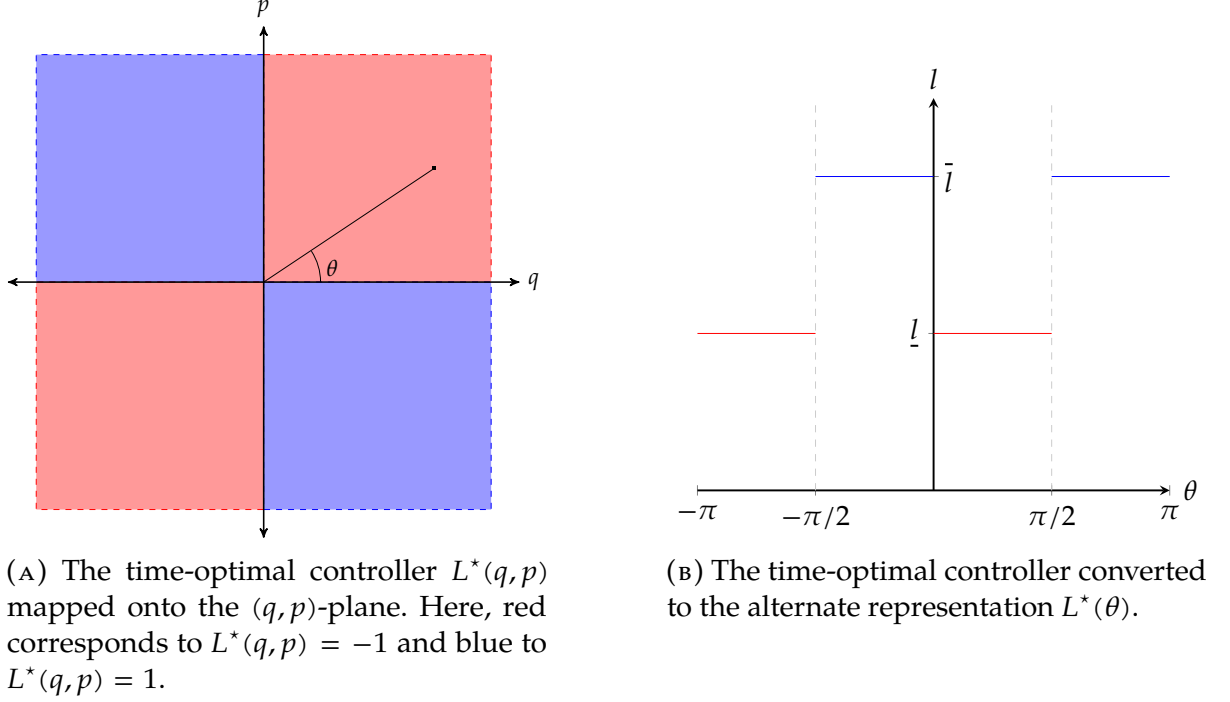


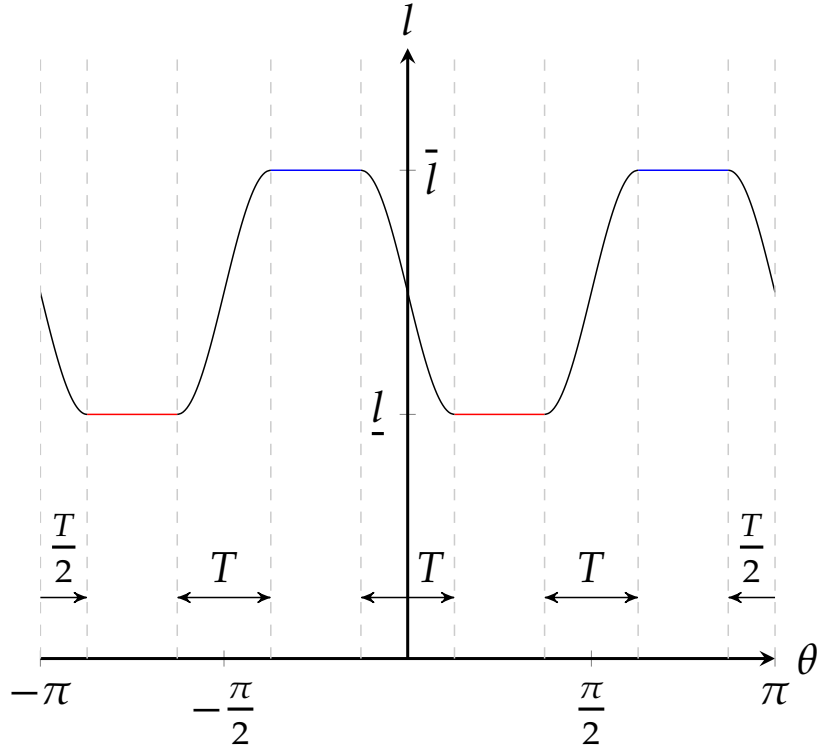
FIGURE 3.3: The time-optimal controller for a standing swing as derived by [16]. The colour red corresponds to standing, blue to squatting, and  $\theta := \arctan_2(p, q)$  is the angle of the VLP phase in the  $(q, p)$ -plane.

the graph of  $L^*(\theta)$ , where now the length varies between  $[L, \bar{L}]$  rather than  $\{-1, 0, 1\}$ .

$$L^*(\theta) := \begin{cases} \bar{l} & \theta \in [-\frac{\pi}{2}, 0] \cup [\frac{\pi}{2}, \pi[ \\ \underline{l} & \theta \in [-\pi, -\frac{\pi}{2}] \cup [0, \frac{\pi}{2}]. \end{cases} \quad (3.4)$$

We now define a continuous function which approximates  $L^*(\theta)$ . Let  $\Delta l := (\bar{l} - \underline{l})/2$  and  $l_{\text{avg}} := (\bar{l} + \underline{l})/2$ . Let  $T \in ]0, \frac{\pi}{2}]$  be a parameter of our choosing. By intelligently attaching sinusoids of frequency  $\omega = \frac{\pi}{T}$  to  $L^*(\theta)$  (see Figure 3.4), we get a family of  $C^1$  constraints  $L_T(\theta)$  parameterized by  $T$ :

$$L_T(\theta) := \begin{cases} \bar{l} & \theta \in \left[-\frac{\pi}{2} + \frac{T}{2}, -\frac{T}{2}\right] \cup \left[\frac{\pi}{2} + \frac{T}{2}, \pi - \frac{T}{2}\right] \\ \underline{l} & \theta \in \left[-\pi + \frac{T}{2}, -\frac{\pi}{2} - \frac{T}{2}\right] \cup \left[\frac{T}{2}, \frac{\pi}{2} - \frac{T}{2}\right] \\ -\Delta l \sin(\omega(\theta + \pi)) + l_{\text{avg}} & \theta \in \left[-\pi, -\pi + \frac{T}{2}\right] \\ -\Delta l \sin(\omega\theta) + l_{\text{avg}} & \theta \in \left[-\frac{T}{2}, \frac{T}{2}\right] \\ \Delta l \sin(\omega(\theta - a)) + l_{\text{avg}} & \theta \in \left[a - \frac{T}{2}, a + \frac{T}{2}\right] \text{ for } a \in \left\{-\frac{\pi}{2}, \frac{\pi}{2}\right\} \\ -\Delta l \sin(\omega(\theta - \pi)) & \theta \in \left[\pi - \frac{T}{2}, \pi\right]. \end{cases} \quad (3.5)$$


 FIGURE 3.4: The continuous VLP constraint  $l = L_T(\theta)$ .

This family of constraints approximates  $L^*(\theta)$  because

$$\lim_{T \rightarrow 0} L_T(\theta) = L^*(\theta).$$

Unfortunately, while  $L_T(\theta)$  is continuously-differentiable, it is not twice-differentiable for most values of  $T$ . If we wish to use it as a VNHC, we must ensure that either the generalized forces  $\tau$  acting on  $p_l$  can be discontinuous (which is certainly achievable by humans), or we must find a value of  $T$  where this constraint is at least  $C^2$ . Thankfully, setting  $T = \frac{\pi}{2}$  yields the smooth function  $L_{\frac{\pi}{2}}(\theta)$ , which can be simplified from (3.5) into

$$L_{\frac{\pi}{2}}(\theta) = -\Delta l \sin(2\theta) + l_{\text{avg}}. \quad (3.6)$$

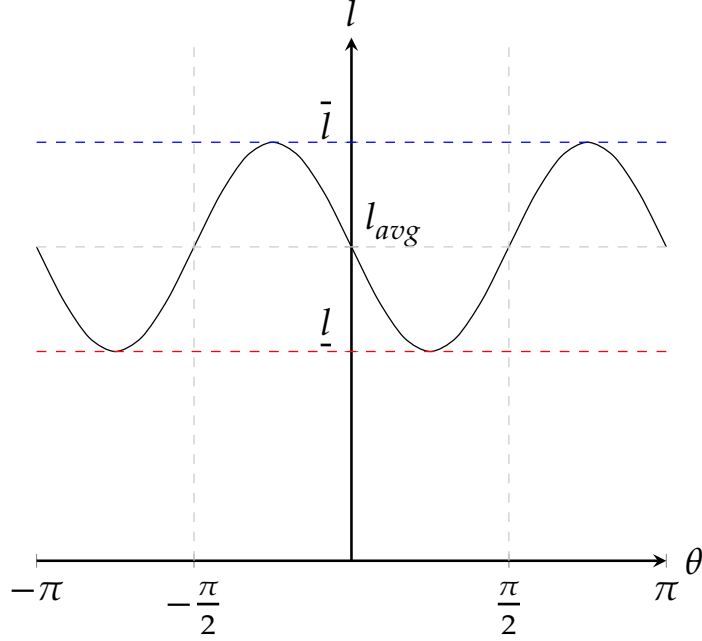
This smooth constraint is plotted for demonstration in Figure 3.5.

Because  $L_{\frac{\pi}{2}}(\theta)$  is smooth and it approximates  $L^*(\theta)$ , we set our VNHC to be

$$h(\mathbf{q}, \mathbf{p}) = l - L_{\frac{\pi}{2}}(\theta(q, p)).$$

What remains is to prove this injects energy into the VLP. As part of the proof, we will




 FIGURE 3.5: The smoothed VLP constraint  $l = L_{\frac{\pi}{2}}(\theta)$ .

require the following lemma.

**Lemma 3.1.** *For any  $x, y \in \mathbb{R}$ ,*

$$\operatorname{sgn}(x^3 - y^3) = \operatorname{sgn}(x - y).$$

*Proof.* Observe that  $x^3 - y^3 = (x - y)(x^2 + xy + y^2)$ . The inequality  $x^2 + xy + y^2 \geq 0$  holds because

$$x^2 + xy + y^2 = \left(x + \frac{y}{2}\right)^2 + \frac{3y^2}{4} \geq 0,$$

which proves the lemma.  $\square$

Supposing the initial condition of the VLP is not an equilibrium, we will show that the constrained dynamics trace out a curve on the  $(q, p)$ -plane which is diverging from the origin. This implies that the momentum  $p$  is increasing in magnitude whenever the curve hits the  $p$ -axis, which in turn means the VLP is gaining energy on average.

**Theorem 3.2.** *Define  $\theta := \arctan_2(p, q)$ . Let  $L : \mathbb{S}^1 \rightarrow [\underline{l}, \bar{l}]$  be a  $C^2$  function of  $\theta$ . Suppose the initial condition of the VLP's unactuated variables is  $(q_0, p_0) \notin \{(0, 0), (\pm\pi, 0)\}$ . A VNHC of the form  $h(\mathbf{q}, \mathbf{p}) = l - L(\theta)$  injects energy into the VLP if there exists  $l_{avg} \in [\underline{l}, \bar{l}]$  such that*

$$(l_{avg} - L(\theta)) \sin(2\theta) \geq 0 \quad \forall \theta \in \mathbb{S}^1, \quad (3.7)$$

with the property that the inequality is strict except at the coordinate axes. If the inequality is flipped, the VNHC dissipates energy.

*Proof.* Let  $\Gamma$  be the constraint manifold for  $h$ . In negative-time, the dynamics on  $\Gamma$  are

$$f(q, p) = - \begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \begin{bmatrix} -\frac{p}{mL(\theta)^2} \\ mgL(\theta) \sin(q) \end{bmatrix}. \quad (3.8)$$

Let  $D = \Gamma \setminus \{(\pm\pi, 0)\}$  be the domain of interest on which we study this negative-time system. Choose, as a candidate Lyapunov-like function, the energy for the average-length pendulum with zero-potential at the bottom of the swing:

$$E_{\text{avg}}(q, p) := \frac{1}{2} \frac{p^2}{m l_{\text{avg}}^2} + mgl_{\text{avg}}(1 - \cos(q)).$$

This is positive definite at  $(0, 0)$  and has compact sublevel sets on  $D$ . The derivative of  $E_{\text{avg}}$  along (3.8) is

$$\dot{E}_{\text{avg}} = \frac{g \sin(q)p (L(\theta)^3 - l_{\text{avg}}^3)}{l_{\text{avg}}^2 L(\theta)^2}.$$

The sign of  $\sin(q)p$  depends only on the quadrant in the  $(q, p)$ -plane. In fact, it is easy to show that

$$\text{sgn}(\sin(q)p) = \text{sgn}(\sin(2\theta)).$$

Furthermore, by Lemma 3.1 we have

$$\text{sgn}(L(\theta)^3 - l_{\text{avg}}^3) = \text{sgn}(L(\theta) - l_{\text{avg}}).$$

The derivative of  $E_{\text{avg}}$  is nonnegative since

$$\begin{aligned} \text{sgn}(\dot{E}_{\text{avg}}) &= \text{sgn}(\sin(q)p (L(\theta)^3 - l_{\text{avg}}^3)) \\ &= \text{sgn}(\sin(2\theta) (L(\theta) - l_{\text{avg}})) \\ &= -\text{sgn}((l_{\text{avg}} - L(\theta)) \sin(2\theta)) \\ &\leq 0 \text{ (by assumption).} \end{aligned}$$

Thus,  $E_{\text{avg}}$  is a Lyapunov function, which means the negative-time system is stable [42]. The last step of the proof is to show that (3.8) asymptotically converges to  $(0, 0)$ . For

this, we will use a Krasovskii-LaSalle argument [50]. First, we define the zero-set

$$Z = \{(q, p) \in \Gamma \mid \dot{E}_{\text{avg}}(q, p) = 0\}.$$

It is easy to show that  $Z$  is the union of the coordinate axes

$$Z = \mathbb{S}^1 \times \{0\} \cup \{0\} \times \mathbb{R}.$$

Krasovskii-LaSalle tells us that solutions to (3.8) converge to the largest invariant set in  $Z \cap D$ . Since  $f(q, p) = (0, 0)$  only when  $(q, p) = (0, 0)$ , the origin is asymptotically stable on  $D$  for the negative-time system. Hence, the positive-time system is diverging away from the origin in the  $(q, p)$  plane, which means the VLP is gaining energy on average. Flipping the inequality of (3.7) means  $E_{\text{avg}}$  is a Lyapunov function for the positive time system; by the same arguments presented here, the VLP loses energy while converging asymptotically to  $(0, 0)$ .  $\square$

**Corollary.** *Recall that*

$$L_{\frac{\pi}{2}}(\theta) := -\Delta l \sin(2\theta) + l_{\text{avg}},$$

*and define*

$$L_{\frac{\pi}{2}}^-(\theta) := \Delta l \sin(2\theta) + l_{\text{avg}}.$$

*The VNHC  $l = L_{\frac{\pi}{2}}(\theta)$  injects energy into the VLP, while  $l = L_{\frac{\pi}{2}}^-(\theta)$  dissipates energy.*

*Proof.* Both VNHCS satisfy Theorem 3.2 because

$$\left(l_{\text{avg}} - L_{\frac{\pi}{2}}(\theta)\right) \sin(2\theta) = \Delta l \sin^2(2\theta) \geq 0,$$

and

$$\left(l_{\text{avg}} - L_{\frac{\pi}{2}}^-(\theta)\right) \sin(2\theta) = -\Delta l \sin^2(2\theta) \leq 0,$$

where the inequalities are strict everywhere except the coordinate axes.  $\square$

The class of VNHCS which satisfies Theorem 3.2 is illustrated graphically in Figure 3.6. To stabilize specific energy level sets, one simple approach is to switch between injection and dissipation VNHCS when the momentum  $p$  reaches a pre-determined value at the bottom of the swing. For the VNHCS we designed in this chapter, this means toggling between  $L_{\frac{\pi}{2}}(\theta)$  and  $L_{\frac{\pi}{2}}^-(\theta)$ , with some hysteresis to avoid infinite switching.

Theorem 3.2 provides an alternate explanation for why the optimal pumping strategy  $L^*(\theta)$  works so well at injecting energy: it maximizes the derivative of  $E_{\text{avg}}$  under the

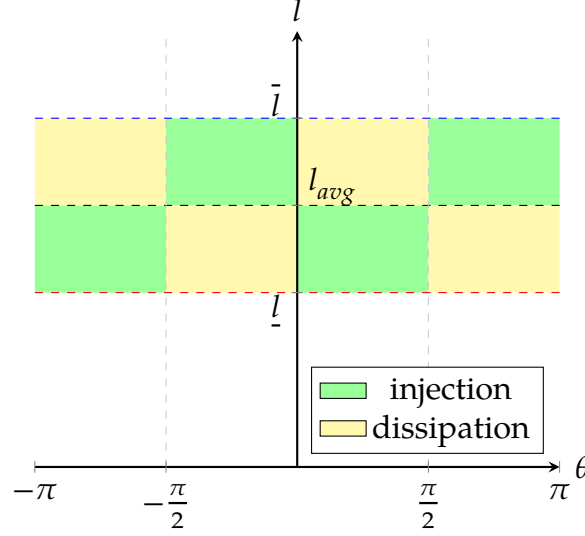


FIGURE 3.6: Any VNHC of the form  $l = L(\theta)$  where  $L(\theta)$  is entirely contained within the green (yellow) regions will inject (dissipate) energy.

restriction  $l \in [\underline{l}, \bar{l}]$ , so that the orbit in the  $(q, p)$ -plane diverges from the origin as fast as possible.

Let us define  $(L^*)^-(\theta)$  by swapping the order of  $\underline{l}$  and  $\bar{l}$  in  $L^*(\theta)$ :

$$(L^*)^-(\theta) := \begin{cases} \underline{l} & \theta \in [-\frac{\pi}{2}, 0[ \cup [\frac{\pi}{2}, \pi[ \\ \bar{l} & \theta \in [-\pi, -\frac{\pi}{2}[ \cup [0, \frac{\pi}{2}[. \end{cases}$$

Since this function *minimizes* the derivative of  $E_{\text{avg}}$  under the restriction  $l \in [\underline{l}, \bar{l}]$ , one might predict that  $(L^*)^-(\theta)$  is the optimal energy dissipation strategy for the VLP. This is, in fact, true. Piccoli and Kulkarni [16] showed that squatting at the lowest point of a swing and standing at the highest (instead of standing and squatting, respectively) produces the time-optimal trajectory for *stopping* a standing swing.

All together, the theory developed in this chapter shows that VNHCS can replicate the time-optimal pumping/dissipation strategies performed by humans on swings. Furthermore, we see that VNHCS are a powerful tool for creating simple energy stabilization techniques based on natural human motion.

### 3.4 Simulation Results

# Chapter 4

## Application of VNHCs: The Acrobot

### 4.1 Motivation

The acrobot is a two-link pendulum, actuated at the center joint (as in Figure 4.1). Since its first description in 1990 [43], the acrobot has become a benchmark problem in control theory; it is an underactuated mechanical system which produces complex nonlinear motion from an easy-to-describe model. The acrobot models a gymnast on a bar, since it represents a torso (top link) and legs (bottom link) with motion generated by the swinging of the legs at the hips. It is also one of the simplest models for a biped walking robot [44].

Controlling the acrobot is a nontrivial task, since it is not feedback linearizable [43]. Several researchers have studied the swing-up problem of driving the acrobot to its equilibrium point above the bar using partial feedback linearization [45], energy-based control [17, 46], and through studying human motion [18, 47].

In gymnastics terminology, a “giant” is the motion a gymnast performs to achieve full rotations around the bar with their body almost fully extended [48]. We are interested in studying the energy stabilization problem for the acrobot by using VNHCs to generate giant motion. The control of giant motion for the acrobot has been studied thoroughly [2, 5, 18], including several studies which use virtual (holonomic) constraints to achieve this behaviour [2, 3, 21]. However, these controllers are neither intuitive nor easy to design: [2] defines a constraint by inverting a trajectory in time onto the state space; [3] requires a cascade controller to stabilize both a constraint and a desired limit cycle in the state space; and [21] enforces the giant by adding an extra state to estimate the velocity, which increases the dimensionality of the problem in a crude approach to using VNHCs.

In this chapter we will design a physically-intuitive VNHC which generates giant

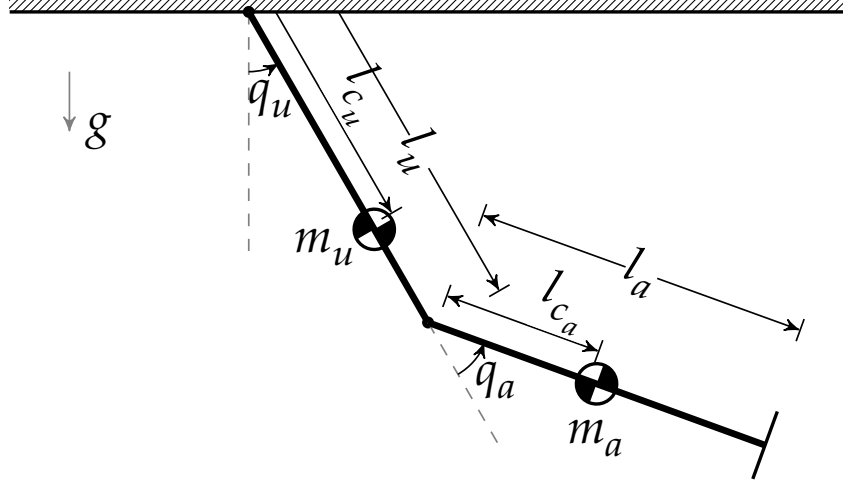


FIGURE 4.1: The general acrobot model, represented by two weighted rods differing in both length and mass.

motion. We will prove that this VNHC injects energy into the acrobot; in the process of completing this proof, we will arrive at a promising method which might be useful for generating desirable VNHCs in the future.

## 4.2 Dynamics of the Acrobot

Suppose we are given an acrobot as in Figure 4.1 modelling a gymnast hanging on a horizontal bar, where the “torso” has moment of inertia  $J_u$  and the “leg” has moment of inertia  $J_a$  (each with respect to their own center of mass). Let  $q_u \in \mathbb{S}^1$  be the shoulder angle and  $q_a \in \mathbb{S}^1$  be the hip angle, where only  $q_a$  is actuated. Collecting them together provides the configuration  $q = (q_u, q_a) \in \mathbb{S}^1 \times \mathbb{S}^1$ . The acrobot has inertia matrix  $D$ , potential function  $P$  (with respect to the horizontal bar), and input matrix  $B$  given as follows [21]:

$$D(q) = \begin{bmatrix} m_a l_u^2 + 2m_a \cos(q_a) l_u l_{c_a} + m_a l_{c_a}^2 + m_u l_{c_u}^2 + J_u + J_a & m_a l_{c_a}^2 + m_a l_u l_{c_a} \cos(q_a) + J_a \\ m_a l_{c_a}^2 + m_a l_u l_{c_a} \cos(q_a) + J_a & m_a l_{c_a}^2 + J_a \end{bmatrix}, \quad (4.1)$$

$$P(q) = g \left( m_a l_{c_a} (1 - \cos(q_u + q_a)) + (m_a l_u + m_u l_{c_u}) (1 - \cos(q_u)) \right), \quad (4.2)$$

$$B(q) = \begin{bmatrix} 0 \\ 1 \end{bmatrix}. \quad (4.3)$$

While this is the most general representation of an acrobot, the Hamiltonian dynamics become too unwieldy for analytically proving results in this chapter. We will

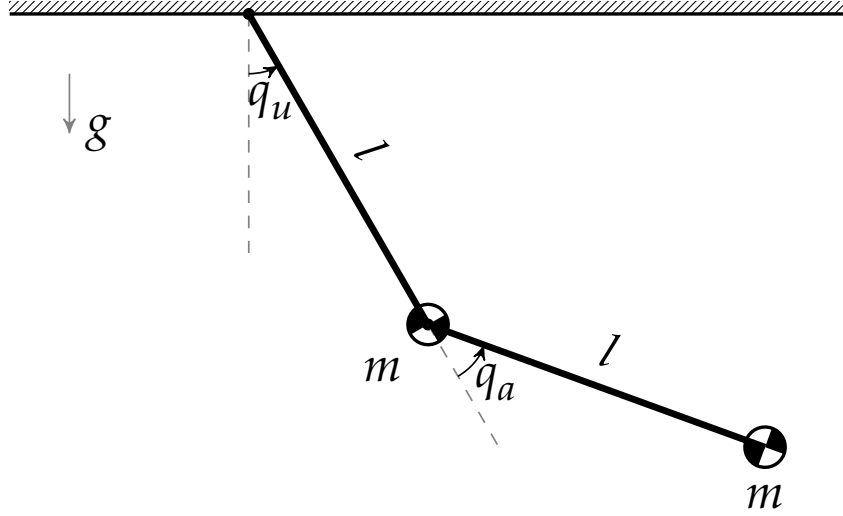


FIGURE 4.2: A simple acrobot has massless rods of equal length  $l$  and equal masses  $m$  at the tips.

therefore simplify the dynamics by assuming the acrobot is comprised of two massless rods of equal length  $l$ , with equal point masses  $m$  at the tips (as in Figure 4.2). We call this type of acrobot a **simple** acrobot. We will also ignore any frictional forces at both the hips and shoulder. Finally, it is important to note that a real gymnast cannot swing their hips in full circles; for this reason, we assume that  $q_a \in [-\bar{q}_a, \bar{q}_a]$  where  $\bar{q}_a \in ]-\pi, \pi[$ . If the acrobot is a robot as opposed to the model of a gymnast,  $\bar{q}_a$  can be used as a control parameter when designing VNHCs.

Taking these assumptions on the model of a simple acrobot, the moments of inertia  $J_u$  and  $J_a$  of the rods vanish. Furthermore,  $l_{c_u} = l_{c_a} = l_u = l_a = l$  and  $m_u = m_a = m$ . Reducing (4.1-4.2) yields the simplified inertia matrix  $D_s$  and potential function  $P_s$ , where

$$D_s(q) = \begin{bmatrix} ml^2 (3 + 2 \cos(q_a)) & ml^2 (1 + \cos(q_a)) \\ ml^2 (1 + \cos(q_a)) & ml^2 \end{bmatrix}, \quad (4.4)$$

$$P_s(q) = -mgl (2 \cos(q_u) + \cos(q_u + q_a)). \quad (4.5)$$

*Notation.* For shorthand, we write  $c_u := \cos(q_u)$ ,  $c_a := \cos(q_a)$ , and  $c_{ua} := \cos(q_u + q_a)$ . Likewise,  $s_u := \sin(q_u)$ ,  $s_a := \sin(q_a)$ , and  $s_{ua} := \sin(q_u + q_a)$ .

Defining  $M(q) := D_s(q)$  and  $V(q) := P_s(q)$ , we find the conjugate of momenta is

$p = (p_u, p_a) = M(q)\dot{q}$ . The dynamics in  $(q, p)$  coordinates are given by

$$\begin{aligned} \mathcal{H}(q, p) &= \frac{1}{2}p^\top M^{-1}(q)p - mgl(2c_u + c_{ua}) \\ \begin{cases} \dot{q} = M^{-1}(q)p \\ \dot{p}_u = -mgl(2s_u + s_{ua}) \\ \dot{p}_a = -\frac{1}{2}p^\top \nabla_{q_a} M^{-1}(q)p - mgl s_{ua} + \tau \end{cases} \end{aligned} \quad (4.6)$$

where the inverse inertia matrix is

$$M^{-1}(q) = \frac{1}{ml^2(2 - c_a^2)} \begin{bmatrix} 1 & -(1 + c_a) \\ -(1 + c_a) & 3 + 2c_a \end{bmatrix} \quad (4.7)$$

### 4.3 Previous Constraint Approaches

### 4.4 The Acrobot Constraint

### 4.5 Proving the Acrobot Gains Energy

### 4.6 Experimental Results



# **Chapter 5**

## **Conclusion**

### **5.1 Limitations of this Work**

### **5.2 Future Research**

# **Appendix A**

## **Matrix Kronecker Product**

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