Feedback Linearizable Discretization of Second-Order Mechanical Systems using Retraction Maps

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Abstract

Mechanical systems are most often described by a set of continuous-time, nonlinear, second-order differential equations (SODEs) of a particular structure governed by the covariant derivative. The digital implementation of controllers for such systems requires a discrete model of the system and hence requires numerical discretization schemes. Feedback linearizability of such sampled systems, however, depends on the discretization scheme employed.

In this thesis, we utilize retraction maps and their lifts to construct feedback linearizable discretizations for SODEs which can be applied to many mechanical systems.

Keywords: geometric integrators, retraction maps, discrete systems, feedback linearization, mechanical systems

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M	manifold
γ	curve/geodesic on M
exp	exponential map on M
TM	tangent bundle of M
$\mathfrak{X}(M)$	space of vector fields on M
X	vector field on M (or TM)
TTM	double tangent bundle of M
φ	diffeomorphism
$T\varphi$	tangent lift of φ
$\mathcal{R}$	retraction map
$\mathcal{D}$	discretization map
R	general map $TM \longrightarrow M$
τ_M	canonical projection map from TM
κ_M	canonical involution map on TTM
$f \circ g$	composition of f and g
Γ^i_{jk}	Christoffel symbols
g_r	control vector fields
e	uncontrolled vector field
∇	affine connection
$\mathbb{I}$	identity map
$\mathfrak{R}$	Riemannian tensor
ann	annihilator – ann $S = \{f \in V^* : f(v) = 0 \quad \text{for all } v \in S\}$ where $S \subset V$
n	default dimension of M
$\langle \cdot, \cdot \rangle$	inner product
∂_x	partial derivative with respect to x
h	step-size of discretization

Chapter 1

Introduction

1.1 Retraction Maps

The notion of a retraction map is fundamental in research areas like optimization theory, machine learning, numerical analysis, and in this context, geometric integrators.
Many mechanical systems usually evolve on manifolds, which naturally requires some method of discretely approximating the dynamics on the manifold (i.e., the geodesic).

In Riemannian geometry, this idea is given by the exponential map. On a Riemannian manifold (M, g), we define $\exp_x : T_xM \longrightarrow M$ as the exponential map at the point x. For instance, if $\gamma : [0,1] \longrightarrow M$ is a unique geodesic on M, and $\gamma(0) = x$, then $\exp_x(v) = \gamma(1)$, where $v \in T_xM$ is the initial velocity of the geodesic at x such that $\dot{\gamma}(0) = v$.

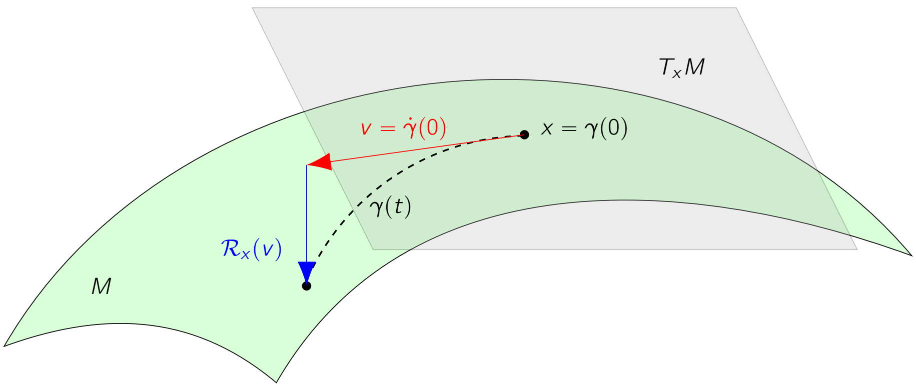


Figure 1.1: Retraction maps: A visualization

Let M be an n dimensional manifold, and TM be its tangent bundle.

Definition 1.1.1. *We define a* **retraction map** *on a manifold M as a smooth map $\mathcal{R} : TM \to M$, such that if $\mathcal{R}_x$ be the restriction of $\mathcal{R}$ to T_xM, then the following properties are satisfied:*

1. *$\mathcal{R}_x(0_x) = x$ where 0_x is the zero element of T_xM.*
2. *$D\mathcal{R}_x(0_x) = T_{0_x}\mathcal{R}_x = \mathbb{I}_{T_xM}$, where $\mathbb{I}_{T_xM}$ is the identity mapping on T_xM.*

Here, the first property is trivial, whereas the second property is known as the **local rigidity condition** since, given $v \in T_xM$, the curve $\gamma_v(t) = \mathcal{R}_x(tv)$ has initial velocity v at x. Hence,

$$\dot{\gamma}_v(t) = \langle \mathrm{D}\mathcal{R}_x(tv), v \rangle \implies \dot{\gamma}_v(0) = \mathbb{I}_{T_xM}(v) = v$$

1.2 Discretization maps

Definition 1.2.1. *A map $\mathcal{D} : U \subset TM \longrightarrow M \times M$ given by*

$$\mathcal{D}(x, v) = \left(R_x^1(v), R_x^2(v)\right)$$

where U is the open neighborhood of the zero section $0_x \in TM$, is called a **discretization map** *on M, if the following properties are satisfied:*

1. $\mathcal{D}(x, 0_x) = (x, x)$
2. $T_{0_x} R_x^2 - T_{0_x} R_x^1 = \mathbb{I}_{T_x M}$*, which is the identity map on $T_x M$ for any $x \in M$.*

Using this definition, one can prove (not included here) that the discretization map $\mathcal{D}$ is a local diffeomorphism around the zero section $0_x \in TM$. This is a crucial property for the construction of geometric integrators, since we need to be able to define $\mathcal{D}^{-1}(x_k, x_{k+1})$.

Remark 1.2.1. *Note that $R_x^i : T_x M \longrightarrow M$ here, is* **not** *a retraction map $\mathcal{R}_x$ in general.*

Remark 1.2.2. *The discretization map $\mathcal{D}$ actually takes a* **single** *element $(x, v) \in TM$ and maps it to a pair of elements $(x_k, x_{k+1}) \in M \times M$.*

Thus, given a vector field $X \in \mathfrak{X}(M)$ on M, i.e., $X : M \longrightarrow TM$ such that $\tau_M \circ X = \mathbb{I}_M$, where $\tau_M : TM \longrightarrow M$ is the canonical projection on the tangent bundle, we can approximate the integral curve by the following first-order discrete equation:

$$hX(\tau_M(\mathcal{D}^{-1}(x_k, x_{k+1}))) = \mathcal{D}^{-1}(x_k, x_{k+1})$$

Hence, given an initial condition x_0, we may be able to solve the discrete equation iteratively to obtain the sequence $\{x_k\}$ which is indeed an approximation of $\{x(kh)\}$, where $x(t)$ is the integral curve of X with initial condition x_0 and time-step h.

1.2.1 Examples

We consider a few examples of discretization maps on $\mathbb{R}^n$ [for $\dot{x}(t) = X(x(t))$]:

Discretization map $\mathcal{D}$	Scheme	Order
$\mathcal{D}(x, v) = (x, x + v)$	Forward Euler $x_{k+1} = x_k + hX(x_k)$	$\mathcal{O}(h)$
$\mathcal{D}(x, v) = (x - v, x)$	Backward Euler $x_k = x_{k+1} - hX(x_{k+1})$	$\mathcal{O}(h)$
$\mathcal{D}(x, v) = \left(x - \frac{v}{2}, x + \frac{v}{2}\right)$	Symmetric Euler $x_{k+1} = x_k + hX\left(\frac{x_k + x_{k+1}}{2}\right)$	$\mathcal{O}(h^2)$

Table 2.1: Examples of discretization maps

1.3 Lifts of discretization maps

As mentioned before, discretization maps are diffeomorphisms around the zero section $0_x \in TM$. This is useful because typically when studying mechanical systems, we would like to define the discretization map on the tangent bundle TM (for Lagrangian frameworks) or the cotangent bundle T^*M (for Hamiltonian frameworks), in order to generate geometric integrators on the manifold.

Thus, since discretization maps can be defined on different manifolds, we denote $\mathcal{D}^{TM} : TM \longrightarrow M \times M$ as a discretization map on M.

1.3.1 Tangent Lifts

Given a smooth map $\varphi : M \longrightarrow N$ between two n-dimenstional manifolds M and N, we can define the **tangent lift** of φ as the map $T\varphi : TM \longrightarrow TN$ such that

$$T\varphi(v_x) = T_x\varphi(v_x) \in T_{\varphi(x)}N$$

where $v_x \in T_xM$ and $T_x\varphi$ is the tangent map of φ, whose matrix is the Jacobian at $x \in M$, in a local chart.

Proposition 1.3.1. *Let M and N be two n-dimensional manifolds, and $\varphi : M \longrightarrow N$ be a smooth map (diffeomorphism). For a given discretization map $\mathcal{D}^{TM}$ on M, the map $\mathcal{D}_\varphi := (\varphi \times \varphi) \circ \mathcal{D}^{TM} \circ T\varphi^{-1}$ is a discretization map on N i.e., $\mathcal{D}_\varphi \equiv \mathcal{D}^{TN} : TN \longrightarrow N \times N$.*

Proof. For any given $y \in N$, we have that

$$\begin{aligned}
\mathcal{D}_\varphi(y, 0_y) &= ((\varphi \times \varphi) \circ \mathcal{D}^{TM} \circ T\varphi^{-1})(y, 0_y) \\
&= ((\varphi \times \varphi) \circ \mathcal{D}^{TM} \circ T\varphi^{-1})(\varphi(x), 0_{\varphi(x)}) \\
&= (\varphi \times \varphi) \circ \mathcal{D}^{TM}(x, 0_x) \\
&= (\varphi \times \varphi)(x, x) = (y, y)
\end{aligned}$$

which proves the first condition. For the second condition, let $v_y \in T_yN$, be a given vector.

$$\begin{aligned}
(T_{0_x}R^2_{x,\varphi} - T_{0_x}R^1_{x,\varphi})(y, u_y) &= \left.\frac{d}{ds}\right|_{s=0} \left(R^2_{x,\varphi}(y, su_y) - R^1_{x,\varphi}(y, su_y)\right) \\
&= \left.\frac{d}{ds}\right|_{s=0} \left(\varphi \circ R^1_x \circ T\varphi^{-1}(y, su_y)\right) - \left(\varphi \circ R^2_x \circ T\varphi^{-1}(y, su_y)\right) \\
&= T_y\varphi\left(\left.\frac{d}{ds}\right|_{s=0} \left[R^1_x(t(T\varphi^{-1}(y, u_y)))\right] - \left[R^2_x(t(T\varphi^{-1}(y, u_y)))\right]\right) \\
&= T_y\varphi(T_y\varphi^{-1}(y, u_y)) = (y, u_y)
\end{aligned}$$

Thus, both the conditions from Definition 1.1.1 are satisfied. □

The above proposition can be visualized as shown below in Figure 3.1.

$$\begin{tikzcd}
TM \arrow[r, "T\varphi"] \arrow[d, "\mathcal{D}^{TM}"'] & TN \arrow[d, "\mathcal{D}^{TN}"] \\
M \times M \arrow[r, "\varphi \times \varphi"'] & N \times N
\end{tikzcd}$$

Figure 3.1: $\mathcal{D}^{TM}$ and $\mathcal{D}^{TN}$ commute as shown

Now, if we suitably lift the discretization map $\mathcal{D} : TM \longrightarrow M \times M$, we can get a discretization map on TM, i.e., we can define $\mathcal{D}^{TTM} : TTM \longrightarrow TM \times TM$ as a discretization map on TM. This construction will provide the geometric framework for integrators for second-order differential equations (SODEs) on manifolds, and consequently, for mechanical systems.

Let M be an n-dimensional manifold, and $\tau_M : TM \longrightarrow M$ be the canonical projection on the tangent bundle. We denote TTM as the **double tangent bundle** of M.

We note that the manifold TTM naturally accepts two different vector bundle structures:

1. The canonical vector bundle with projection $\tau_{TM} : TTM \longrightarrow TM$.
2. The vector bundle given by the projection of the tangent map $T\tau_M : TTM \longrightarrow TM$.

Thus, we denote the canonical involution map $\kappa_M : TTM \longrightarrow TTM$ which is a vector bundle isomorphism, over the identity of TM between the above two vector bundle structures.

This can be seen here: Let (x, v) be the canonical coordinates on TM, and $(x, v, \dot{x}, \dot{v})$ are the corresponding canonical fibered coordinates on TTM. Then,

$$\kappa_M(x, v, \dot{x}, \dot{v}) = (x, \dot{x}, v, \dot{v})$$

Remark 1.3.1. *Why do we need this? Remember that the tangent lift of a vector field X on M does not define a vector field on TM. It is necessary to consider the composition $\kappa_M \circ TX$ to obtain a vector field on TM, and this is called the* **complete lift** *X^c of the vector field X. Hence, a similar technique must be used to lift a discretization map from TM to TTM.*

$$\begin{tikzcd}
TTM \arrow[r, "\mathcal{D}^{TTM}"] \arrow[d, leftrightarrow, "\kappa_M"', "\kappa_M"] & TM \times TM \arrow[d, equal] \\
TTM \arrow[r, "T\mathcal{D}^{TM}"] \arrow[d, "\tau_{TM}"'] & T(M \times M) \arrow[d, "\tau_{M \times M}"] \\
TM \arrow[r, "\mathcal{D}^{TM}"] & M \times M
\end{tikzcd}$$

Figure 3.2: Tangent lift structure of discretization maps

Using the above construction, we can now define the tangent lift of a discretization map.

Proposition 1.3.2. *If $\mathcal{D}^{TM} : TM \longrightarrow M \times M$ is a discretization map on M, then the map defined by $\mathcal{D}^{TTM} = T\mathcal{D}^{TM} \circ \kappa_M$ is a discretization map on TM.*

Proof. For $(x, v, \dot{x}, \dot{v}) \in TTM$, we have that

$$T\mathcal{D}^{TM}(x, v, \dot{x}, \dot{v}) = \left(\mathcal{D}^{TM}(x, v), D_{(x,v)}\mathcal{D}^{TM}(x, v)(\dot{x}, \dot{v})^T\right)$$

and

$$\mathcal{D}^{TTM}(x, \dot{x}, v, \dot{v}) = (\mathcal{D}^{TM}(x, v), D_{(x,v)}\mathcal{D}^{TM}(\dot{x}, \dot{v})^T)$$

Using the properties defined in Definition (1.1.1),

1. We know that $\mathcal{D}^{TM}(x,0) = (x,x)$ for all $x \in M$. Thus,

$$\begin{aligned}\mathcal{D}^{TTM}(x,\dot{x},0,0) &= \big(\mathcal{D}^{TM}(x,0), D_{(x,0)}\mathcal{D}^{TM}(\dot{x},0)\big)\\ &= (x,x,\dot{x},\dot{x}) \equiv (x,\dot{x},x,\dot{x})\end{aligned}$$

   where we trivially identify $T(M\times M) \equiv TM \times TM$.

2. For the rigidity property, we know that

$$\mathcal{D}^{TTM}(x,\dot{x},v,\dot{v}) = \Big((TR^1)_{(x,\dot{x})}(v,\dot{v}), (TR^2)_{(x,\dot{x})}(v,\dot{v})\Big)$$

   So, we need to compute

$$T_{(0,0)_{(x,\dot{x})}}(TR^a)_{(x,\dot{x})}(x,\dot{x}) : T_{(x,\dot{x})}TM \longrightarrow T_{(x,\dot{x})}TM$$

   for $a = 1,2$, to prove that the map $T(TR^2)_{(x,\dot{x})} - T(TR^1)_{(x,\dot{x})}$ is the identity map at the zero section $(0,0)_{(x,\dot{x})}$, from $T_{(x,\dot{x})}TM$ to itself.

   We can calculate

$$\left.\frac{d}{ds}\right|_{s=0} (R^a_x(sv), \partial_x R^a_x(sv)\dot{x} + \partial_v R^a_x(sv)s\dot{v})$$

   At $(x,\dot{x},0,0)$, the map $T_{(0,0)_{(x,\dot{x})}}(TR^a)_{(x,\dot{x})}$ is thus given by:

$$\begin{pmatrix} \partial_{v^j}(R^a)^i(x,0) & 0 \\ \partial_{x^k}\partial_{v^j}(R^a)^i(x,0)\dot{x}^k & \partial_{v^j}(R^a)^i(x,0)\end{pmatrix}$$

   Thus, using the properties of the discretization map $\mathcal{D}$, we have the Jacobian matrix of $(TR^2)_{(x,\dot{x})} - (TR^1)_{(x,\dot{x})}$ at $(0,0)_{(x,\dot{x})}$ as:

$$\begin{pmatrix} \partial_v(R^2-R^1)(x,0) & 0 \\ \partial_x(\partial_v(R^2-R^1)(x,0))\dot{x} & \partial_v(R^2-R^1)(x,0)\end{pmatrix} = \mathbb{I}_{2n\times 2n}$$

   since $\partial_v(R^2-R^1)(x,0) = \mathbb{I}_{n\times n}$ which also implies $\partial_x(\partial_v(R^2-R^1))(x,0) = 0$

$\square$

1.3.2 Example

Let us consider the midpoint rule as an example. Thus, if M is a vector space, $\mathcal{D} : TM \longrightarrow M\times M$ is the discretization map given by $\mathcal{D}(x,v) = \big(x - \frac{1}{2}v, x + \frac{1}{2}v\big)$. We can also compute the inverse map as $\mathcal{D}^{-1}(x_k, x_{k+1}) = \left(\dfrac{x_k + x_{k+1}}{2}, x_{k+1} - x_k\right)$.

To define the tangent lift of $\mathcal{D}$, denoted by $\mathcal{D}^{TTM} : TTM \longrightarrow TM \times TM$, we need to compute the Jacobian of $\mathcal{D}$,

$$D_{(x,v)}\mathcal{D} = \begin{pmatrix} \mathbb{I} & -\frac{1}{2}\mathbb{I} \\ \mathbb{I} & \frac{1}{2}\mathbb{I} \end{pmatrix}$$

which yields the tangent lift of $\mathcal{D}$ as:

$$\begin{aligned} \mathcal{D}^{TTM}(x, \dot{x}, v, \dot{v}) &= (T\mathcal{D} \circ \kappa_M)(x, \dot{x}, v, \dot{v}) = T\mathcal{D}(x, v; \dot{x}, \dot{v}) \\ &= \left(x - \frac{1}{2}v, x + \frac{1}{2}v; \dot{x} - \frac{1}{2}\dot{v}, \dot{x} + \frac{1}{2}\dot{v} \right) \\ &\equiv \left(x - \frac{1}{2}v, \dot{x} - \frac{1}{2}\dot{v}; x + \frac{1}{2}v, \dot{x} + \frac{1}{2}\dot{v} \right) \end{aligned}$$

We can also obtain the inverse map of $\mathcal{D}^{TTM}$ as

$$\left(\mathcal{D}^{TTM}\right)^{-1}(x_k, v_k; x_{k+1}, v_{k+1}) = \left(\frac{x_k + x_{k+1}}{2}, \frac{v_k + v_{k+1}}{2}; x_{k+1} - x_k, v_{k+1} - v_k \right)$$

1.4 Generalizing construction of discretization maps

In Proposition 1.3.1, we have seen how a discretization map $\mathcal{D}_\varphi$ can be constructed on a manifold N given a diffeomorphism $\varphi : M \longrightarrow N$ and a discretization map $\mathcal{D}^{TM}$ on M. This construction can be extended to TTN as well.

This is useful because, often we deal with *change of coordinates* in mechanical systems, which may simplify, or attribute more meaning to the system. Hence, if we choose to define a discretization scheme on the new coordinates, we must be able to lift it back to the original manifold.

$$\begin{tikzcd}
TM \arrow[r, equal] \arrow[dddr, bend right, "\mathcal{D}^{TM}"'] & TM \arrow[r, "T\varphi"] & TN \arrow[r, equal] & TN \arrow[dddl, bend left, "\mathcal{D}^{TN}"] \\
TTM \arrow[u, "T\tau_M"] \arrow[r, leftrightarrow, "\kappa_M"] \arrow[d, "T\mathcal{D}^{TM}"'] & TTM \arrow[u, "\tau_{TM}"] \arrow[r, "TT\varphi"] \arrow[d, "\mathcal{D}^{TTM}"'] & TTN \arrow[u, "\tau_{TN}"'] \arrow[r, leftrightarrow, "\kappa_N"] \arrow[d, "\mathcal{D}^{TTN}"] & TTN \arrow[u, "T\tau_N"'] \arrow[d, "T\mathcal{D}^{TN}"] \\
T(M \times M) \arrow[r, equal] & TM \times TM \arrow[r, "T\varphi \times T\varphi"] \arrow[d, "\tau_{M\times M}"'] & TN \times TN \arrow[r, equal] \arrow[d, "\tau_{N\times N}"] & T(N \times N) \\
 & M \times M \arrow[r, "\varphi \times \varphi"] & N \times N &
\end{tikzcd}$$

Figure 4.1: $\mathcal{D}^{TTM}$ and $\mathcal{D}^{TTN}$ commute as shown.

Let M and N be two n-dimensional manifolds, and $\varphi : M \longrightarrow N$ be a diffeomorphism, which denotes some *change of coordinates*. The questions of importance is the following:

If we wish to have a discretization map $\mathcal{D}^{TN}$ on N, how do we obtain the discretization on the original tangent space TM, i.e., $\mathcal{D}^{TTM}$?

The double commutator in Figure 4.1 explains the procedure as follows:

1. Start with a required discretization map $\mathcal{D}^{TN}$ on N, and a given $\varphi : M \longrightarrow N$.
2. Lift it back (refer Fig. 3.1) to TM to obtain $\mathcal{D}^{TM}$ using:
$$\mathcal{D}^{TM} = (\varphi \times \varphi)^{-1} \circ \mathcal{D}^{TN} \circ T\varphi$$
3. Obtain D^{TTM} by the tangent lift (refer Fig. 3.2) of $\mathcal{D}^{TM}$, i.e.,
$$\mathcal{D}^{TTM} = T\mathcal{D}^{TM} \circ \kappa_M$$

Can we construct $\mathcal{D}^{TTM}$ from $\mathcal{D}^{TTN}$?

Proposition 1.4.1. *Let M and N be n dimensional manifolds and $\varphi(x) = \tilde{x}$, where φ is a diffeomorphism and $x \in M, \tilde{x} \in N$. Let TM and TN be the tangent bundles of M and N, respectively. By definition, if $(x, \dot{x}) \in TM$ and $(\tilde{x}, \dot{\tilde{x}}) \in TN$, then $T\varphi(x, \dot{x}) = (\tilde{x}, \dot{\tilde{x}})$ through the same diffeomorphism. For a given discretization map $\mathcal{D}^{TTM}$ on TM, $\mathcal{D}^{TTN} := (T\varphi \times T\varphi) \circ \mathcal{D}^{TTM} \circ TT\varphi^{-1}$ is a discretization map on TN (refer Figure 4.1).*

Proof. For any given $(\tilde{x}, \dot{\tilde{x}}) \in TN$, we have that:

$$\begin{aligned}\mathcal{D}^{TTN}(\tilde{x}, \dot{\tilde{x}}, 0, 0) &= \left((T\varphi \times T\varphi) \circ \mathcal{D}^{TTM} \circ TT\varphi^{-1}\right)(\tilde{x}, \dot{\tilde{x}}, 0, 0) \\ &= (T\varphi \times T\varphi) \circ \mathcal{D}^{TTM}(x, \dot{x}, 0, 0) \\ &= (T\varphi \times T\varphi)(x, \dot{x}, x, \dot{x}) = (\tilde{x}, \dot{\tilde{x}}, \tilde{x}, \dot{\tilde{x}})\end{aligned}$$

which proves the first condition in (1.1.1).

Now, for coordinates $(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}}) \in TTN$,

$$\begin{aligned}&(T_{(0_{\tilde{x}}, 0_{\dot{\tilde{x}}})}(TR^2_\varphi)_{(\tilde{x}, \dot{\tilde{x}})} - T_{(0_{\tilde{x}}, 0_{\dot{\tilde{x}}})}(TR^1_\varphi)_{(\tilde{x}, \dot{\tilde{x}})})(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}}) \\ &= \left.\frac{d}{ds}\right|_{s=0} [(T\varphi \circ (TR^1) \circ TT\varphi^{-1})(\tilde{x}, \dot{\tilde{x}}, s\tilde{y}, s\dot{\tilde{y}}) \\ &- (T\varphi \circ (TR^2) \circ TT\varphi^{-1})(\tilde{x}, \dot{\tilde{x}}, s\tilde{y}, s\dot{\tilde{y}})] \\ &= T_{(\tilde{x}, \dot{\tilde{x}})} T\varphi \begin{pmatrix} \left.\frac{d}{ds}\right|_{s=0} [(TR^1)(s(TT\varphi^{-1})(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}})) \\ -(TR^2)(s(TT\varphi^{-1})(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}}))] \end{pmatrix} \\ &= T_{(\tilde{x}, \dot{\tilde{x}})} T\varphi((TT\varphi^{-1})(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}})) = (\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}})\end{aligned}$$

which proves the second condition in (1.1.1).

Note that $R : TM \longrightarrow M \times M$ and $R_\varphi : TN \longrightarrow N \times N$ are retraction maps on M and N respectively. Thus, using the linearity of the map $TT\varphi$, we prove that $\mathcal{D}^{TTN}$ is indeed a discretization map on TN. ◻

Chapter 2

Mechanical Control Systems

Mechanical systems are usually described by nonlinear second-order differential equations (SODEs). In this chapter, we will discuss the geometric formulation of SODEs and their discretization. We will define different classes of mechanical systems, and how a specific class of mechanical systems can be controlled using a technique called *feedback linearization*.

2.1 Second-order differential equations (SODEs)

Let $x \in M$ and $(x, \dot{x}) \in TM$ be the coordinates on the manifold M and the induced coordinates on the tangent bundle of M, respectively. We know that a second-order differential equation is a vector field X such that $\tau_{TM}(X) = T\tau_M(X)$. This implies that the vector field X on TM is a section of the second-order tangent bundle TTM. Locally, if we take coordinates (x^i) on M and induced coordinates $(x^i, \dot{x}^i)$ on TM, then:

$$X = \dot{x}^i \frac{\partial}{\partial x^i} + X^i(x^i, \dot{x}^i)\frac{\partial}{\partial \dot{x}^i} \tag{1.1}$$

To find the integral curves of X is equivalent to solving the SODE:

$$\frac{d^2}{dt^2}x(t) = X\left(x(t), \frac{d}{dt}x(t)\right) \tag{1.2}$$

Now, we wish to discretize this using the notion of the discretization map on TM. We would like to tangently lift a discretization on M to obtain $\mathcal{D}^{TTM} : TTM \longrightarrow TM \times TM$ as defined in Proposition 1.4.1. This yields the following numerical scheme [[1]]:

$$\begin{aligned} hX\left(\left(\tau_{TM} \circ \left(\mathcal{D}^{TTM}\right)^{-1}\right)(x_k, y_k; x_{k+1}, y_{k+1})\right) \\ = \left(\mathcal{D}^{TTM}\right)^{-1}(x_k, y_k; x_{k+1}, y_{k+1}) \end{aligned} \tag{1.3}$$

2.1.1 Example

Let us say we choose the midpoint discretization on $N = \mathbb{R}^n$, denoted by $\mathcal{D}$ of the following form:

$$\mathcal{D}^{TN}(\tilde{x}, \tilde{y}) = \left(\tilde{x} - \frac{\tilde{y}}{2}, \tilde{x} + \frac{\tilde{y}}{2}\right) \tag{1.4}$$

for some $(\tilde{x}, \tilde{y}) \in TN$. Thus, similar to Example 1.3.2, we have:

$$\mathcal{D}^{TTN}(\tilde{x}, \dot{\tilde{x}}, \tilde{y}, \dot{\tilde{y}}) = \left(\tilde{x} - \frac{\tilde{y}}{2}, \tilde{x} + \frac{\tilde{y}}{2}, \dot{\tilde{x}} - \frac{\dot{\tilde{y}}}{2}, \dot{\tilde{x}} + \frac{\dot{\tilde{y}}}{2}\right) \tag{1.5}$$

which is a discretization on TN.

Now, to lift $\mathcal{D}^{TTN}$ to obtain $\mathcal{D}^{TTM}$, we use Proposition 1.4.1, which gives:

$$\mathcal{D}^{TTM} = (T\phi \times T\phi)^{-1} \circ \mathcal{D}^{TTN} \circ TT\phi \tag{1.6}$$

which is also a discretization map on TM.

Using the numerical scheme from Equation (1.3), we obtain:

$$\begin{aligned} \frac{x_{k+1} - x_k}{h} &= \frac{y_{k+1} + y_k}{2}, \\ \frac{y_{k+1} - y_k}{h} &= X\left(\frac{x_k + x_{k+1}}{2}, \frac{y_k + y_{k+1}}{2}\right) \end{aligned} \tag{1.7}$$

which is the numerical scheme for a symmetric discretization of the SODE (1.2).

2.2 Mechanical control systems

We define a mechanical control system as proposed in [[3]].

Definition 2.2.1. *A mechanical control system $(\mathcal{MS})_{(n,m)}$ is defined by a 4-tuple $(M, \nabla, \mathfrak{g}, e)$ where:*

- *M is an n-dimensional manifold*
- *∇ is a symmetric affine connection on M*
- *$\mathfrak{g} = \{g_1, \ldots, g_m\}$ is an m-tuple of control vector fields on M*
- *e is an uncontrolled vector field on M*

$(\mathcal{MS})_{(n,m)}$ can be represented by the differential equation:

$$\nabla_{\dot{x}}\dot{x} = e(x) + \sum_{r=1}^{m} g_r(x)u_r \tag{2.1}$$

Or equivalently in local coordinates $x = (x^1, \ldots, x^n)$ on M,

$$\ddot{x}^i = -\Gamma^i_{jk}(x)\dot{x}^j\dot{x}^k + e^i(x) + \sum_{r=1}^{m} g^i_r(x)u_r \tag{2.2}$$

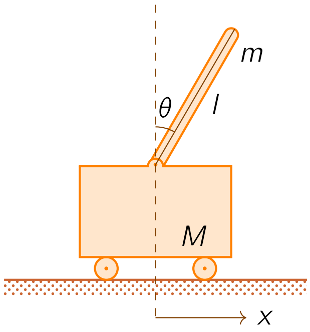
where Γ^i_{jk} are the Christoffel symbols corresponding to the Coriolis and centrifugal force terms, $e(x)$ is the uncontrolled vector field, $g_r(x)$ are the controlled vector fields in Q.

If we write this as two first-order differential equations:

$$\begin{aligned} \dot{x}^i &= y^i; \\ \dot{y}^i &= -\Gamma^i_{jk}(x)y^jy^k + e^i(x) + \sum_{r=1}^{m} g^i_r(x)u_r \end{aligned} \tag{$\mathcal{MS}$}$$

2.2.1 Example

Consider the classic example of an inverted pendulum on a cart:



The equations of motion for this system are given by:

$$
\begin{aligned}
(M+m)\ddot{x} + ml\cos\theta\ddot{\theta} - ml\sin\theta(\dot{\theta})^2 &= F \\
ml\cos\theta\ddot{x} + \frac{4}{3}ml^2\ddot{\theta} - mgl\sin\theta &= 0
\end{aligned}
\tag{2.3}
$$

where F is the force applied to the cart.

Let us define $x^1 = x, x^2 = \theta$ and we denote $\dot{x}^1 = y^1, \dot{x}^2 = y^2$. We can write the above equations as:

$$
\begin{aligned}
\dot{x}^1 &= y^1 \\
\dot{x}^2 &= y^2 \\
\dot{y}^1 &= -\Gamma^1_{22}y^2y^2 + e^1 + g^1u \\
\dot{y}^2 &= -\Gamma^2_{22}y^2y^2 + e^2 + g^2u
\end{aligned}
\tag{2.4}
$$

where, for $\eta = \dfrac{3}{ml^2\left(4(M+m) - 3m\cos^2\theta\right)}$ we have:

$$
\begin{aligned}
\Gamma^1_{22} &= \left(-\frac{4}{3}m^2l^3\sin^3\theta\right)\eta & \Gamma^2_{22} &= \left(\frac{1}{2}m^2l^2\sin 2\theta\right)\eta \\
e^1 &= \left(\frac{1}{2}m^2l^2g\sin 2\theta\right)\eta & e^2 &= \left((M+m)mgl\sin\theta\right)\eta \\
g^1 &= \left(\frac{4}{3}ml^2\right)\eta & g^2 &= \left(-ml\cos\theta\right)\eta
\end{aligned}
$$

Thus, this system in (2.4) is in the form of a mechanical control system ($\mathcal{MS}$).

It is be interesting to note that this system is mechanically feedback linearizable only if the input is given to the pendulum (as torque) and not the cart!

Chapter 3

Feedback Linearization

3.1 Introduction

Feedback linearization has been successfully applied to a wide range of nonlinear systems, including robotic manipulators, aerospace vehicles, and chemical processes. It provides a systematic approach to control design and can significantly improve the performance and stability of nonlinear systems.

In the following sections, we will explore the mathematical foundations of feedback linearization, discuss its application to various systems, and present examples to illustrate its effectiveness. We will also look at an interesting class of systems called **Mechanically Feedback Linearizable** systems, which can be controlled using feedback linearization techniques.

3.2 Feedback Linearization

Feedback linearization is a control technique used to transform a nonlinear system into an equivalent linear system through a change of variables and a suitable feedback control law. This method allows the application of linear control techniques to nonlinear systems, which can simplify the design and analysis of control systems.

Consider the following continuous-time dynamical system (for $t \in [0, T], T > 0$):

$$\frac{d}{dt}x(t) = X(x(t), u(t)) \tag{2.1}$$

on an n-dimensional manifold M, where $X(\cdot, u) \in \mathfrak{X}(M)$ is a vector field, for each $u \in U \subset \mathbb{R}^n$. A point $(x_0, u_0) \in M \times U$ is called an equilibrium point of the system (2.1) if $X(x_0, u_0) = 0$.

Definition 3.2.1. *Let M and N be two n-dimensional manifolds and $\varphi : M \longrightarrow N$ be a diffeomorphism. Let $X \in \mathfrak{X}(M)$ be a vector field on M. Then, $X_\varphi = T\varphi \circ X \circ \varphi^{-1}$ is a vector field on N (push-forward) for the dynamical system*

$$\frac{d}{dt}\tilde{x}(t) = X_\varphi(\tilde{x}(t), u(t)) \tag{2.2}$$

with $\tilde{x}(0) = \varphi(x(0))$ satisfying $\tilde{x}(t) = \varphi(x(t)), t \in [0, T]$.

Let $x \in \mathcal{O}(x_0)$ and $u \in \mathcal{O}(u_0)$ be open balls (neighborhood) around x_0 and u_0 in M and U respectively. Let $x \longmapsto \varphi(x) = \tilde{x} \in N := \mathbb{R}^n$ be a diffeomorphism, and $(x, u) \longmapsto \psi(x, u) := v \in \mathbb{R}^m$ such that for each fixed x, $\psi(x, \cdot) : U \longrightarrow \mathbb{R}^n$ is invertible. Thus, a dynamical system (2.1) is said to be (locally) feedback linearizable around (x_0, u_0) on $\mathcal{O}(x_0) \times \mathcal{O}(u_0)$

if there exists matrices $A \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$ such that $X_\varphi(\tilde{x}, v) = A\tilde{x} + Bv$, with $v = \psi(\varphi^{-1}(\tilde{x}), u)$. The feedback linearized dynamical system is given by:

$$\frac{d}{dt}\tilde{x}(t) = A\tilde{x}(t) + Bv(t) \tag{2.3}$$

3.2.1 Example

Consider the following continuous-time dynamical system:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} (1 + 2u(t))x_2(t) \\ u(t) \end{pmatrix} \tag{2.4}$$

Taking $\tilde{x}_1 = x_1 - x_2^2$ and $\tilde{x}_2 = x_2$, we get the diffeomorphism $\varphi(x_1, x_2) = \left(x_1 - x_2^2, x_2\right)$, we get the feedback linearized system:

$$\begin{pmatrix} \dot{z}_1(t) \\ \dot{z}_2(t) \end{pmatrix} = \begin{pmatrix} z_2(t) \\ u(t) \end{pmatrix} \tag{2.5}$$

3.2.2 Discrete Feedback Linearization

Let's take a detour and check if a discretized system is feedback linearizable. Consider the same example as above.

First, we consider the forward Euler discretization scheme $\mathcal{D}(x, v) = (x, x + v)$. This gives a discrete-time system:

$$\begin{pmatrix} x_{1,k+1} \\ x_{2,k+1} \end{pmatrix} = \begin{pmatrix} x_{1,k} \\ x_{2,k} \end{pmatrix} + h \begin{pmatrix} (1 + 2u_k)x_{2,k} \\ u_k \end{pmatrix} \tag{2.6}$$

Taking the same diffeomorphism φ as before, we get:

$$\begin{pmatrix} z_{1,k+1} \\ z_{2,k+1} \end{pmatrix} = \begin{pmatrix} z_{1,k} + hz_{2,k} - h^2u_k^2 \\ z_{2,k} + hu_k \end{pmatrix} \tag{2.7}$$

Thus, we see that it is NOT feedback linearizable.

Now, let's consider an alternate discretization which yields the discrete system:

$$\begin{pmatrix} x_{1,k+1} \\ x_{2,k+1} \end{pmatrix} = \begin{pmatrix} x_{1,k} \\ x_{2,k} \end{pmatrix} + h \begin{pmatrix} (1 + 2u_k)x_{2,k} \\ u_k \end{pmatrix} + h^2 \begin{pmatrix} u_k^2 \\ 0 \end{pmatrix} \tag{2.8}$$

Again taking the same diffeomorphism φ, we get:

$$\begin{pmatrix} z_{1,k+1} \\ z_{2,k+1} \end{pmatrix} = \begin{pmatrix} z_{1,k} + hz_{2,k} \\ z_{2,k} + hu_k \end{pmatrix} \tag{2.9}$$

which is indeed feedback linearizable.

Thus, we see that the choice of discretization scheme can affect the feedback linearizability of a system.

3.3 Feedback Linearizable Discretization

As seen from above, the following question persists: *Given a feedback linearizable continuous-time system, is it possible to construct a numerical discretization which is also feedback linearizable?*

Yes. We can do this by using the notion of lifts of discretization maps, since the feedback linearization is a diffeomorphism. Invoking the proposition (1.3.1), we can construct a discretization scheme:

$$\left(\mathcal{D}^{TM}\right)^{-1}(x_k, x_{k+1}) = hX\left(\tau_M\left(\left(\mathcal{D}^{TM}\right)^{-1}(x_k, x_{k+1}), u_k\right)\right) \tag{3.1}$$

$$\mathcal{D}^{TN} = (T\varphi \times T\varphi)^{-1} \circ \mathcal{D}^{TM} \circ TT\varphi \tag{3.2}$$

This allows us to define a scheme on TM for a choice of discretization on TN, and a given change of coordinates φ via feedback linearization.

3.4 Mechanical Feedback Linearization

Mechanical Feedback Linearization (MF-Linearization) is the application of feedback linearization to nonlinear mechanical systems. Mechanical systems usually evolve on a configuration manifold M, hence feedback linearization would usually not yield a linear system which preserves the mechanical structure (due to the affine connection).

However, there exists a class of mechanical systems, called the **MF-Linearizable** systems, for which feedback linearization is possible:

Definition 3.4.1. *A mechanical control system $(\mathcal{MS})_{(n,m)} = (M, \nabla, \mathfrak{g}, e)$ is called MF-linearizable if it is MF-equivalent to a linear mechanical system $(\mathcal{LMS})_{(n,m)} = (\mathbb{R}^n, \overline{\nabla}, \mathfrak{b}, A\tilde{x})$, where $\overline{\nabla}$ is an affine connection with the Christoffel symbols zero ($\overline{\nabla}$ is a flat connection) and $\mathfrak{b} = \{b_1, \ldots, b_m\}$ are constant vector fields. In other words, there exists $(\varphi, \alpha, \beta, \gamma) \in MF$ such that*

$$\begin{aligned}
\varphi : M \longrightarrow N \quad \varphi(x) &= \tilde{x} \\
\varphi_*\left(\nabla - \sum_{r=1}^{m} g_r \otimes \gamma^r\right) &= \overline{\nabla} \\
\varphi_*\left(\sum_{r=1}^{m} \beta_s^r g_r\right) &= b_s,\ 1 \leqslant s \leqslant m \\
\varphi_*\left(e + \sum_{r=1}^{m} g_r \alpha^r\right) &= A\tilde{x}
\end{aligned} \tag{4.1}$$

Equivalently, we have the corresponding linear mechanical system $(\mathcal{LMS})_{(n,m)}$ as:

$$\dot{\tilde{x}} = \tilde{y}; \ \dot{\tilde{y}} = A\tilde{x} + \sum_{s=1}^{m} b_s \tilde{u}_s \tag{4.2}$$

3.4.1 Determining MF-Linearizability

Given a mechanical system, how do we determine if it falls under the class of mechanically feedback linearizable systems?

From the definition in (2.1), we can define the following distributions:

$$\begin{aligned} \mathcal{E}^0 &= \mathrm{span}\{g_r, 1 \leqslant r \leqslant m\} \\ \mathcal{E}^j &= \mathrm{span}\{\mathrm{ad}_e^i g_r, 1 \leqslant r \leqslant m, 0 \leqslant i \leqslant j\} \end{aligned} \tag{4.3}$$

Thus, we state the following theorem:

Theorem 3.4.1. *A mechanical system $(\mathcal{MS})_{(n,m)}$ is said to be mechanical feedback (MF) linearizable, locally around $x_0 \in M$ if and only if, in the neighborhood of x_0, it satisfies the following conditions:*

- $(ML1)$ *$\mathcal{E}^0$ and $\mathcal{E}^1$ are of constant rank*
- $(ML2)$ *$\mathcal{E}^0$ is involutive*
- $(ML3)$ *ann $\mathcal{E}^0 \subset$ ann $\mathfrak{R}$*
- $(ML4)$ *ann $\mathcal{E}^0 \subset$ ann ∇g_r for all $r : 1 \leqslant r \leqslant m$*
- $(ML5)$ *ann $\mathcal{E}^1 \subset$ ann $\nabla^2 e$*

where $\mathfrak{R}$ is the Riemannian curvature tensor and ann is the annihilator.

Remark 3.4.1. *The above conditions $(ML1)$–$(ML5)$ are valid without the assumption of controllability of the linearized mechanical system*

We can also define the feedback linearization for different classes of mechanical systems. The following proposition is explicitly stated for planar mechanical systems where $n = 2$. (refer [2]).

Proposition 3.4.2. *A planar mechanical system $(\mathcal{MS})_{(2,1)}$ is locally MF-linearizable at $x_0 \in M$ to a controllable $(\mathcal{LMS})_{(2,1)}$, if and only if it satisfies the following conditions:*

1. $(MD1)$ *g and $ad_e g$ are independent*
2. $(MD2)$ $\nabla_g g \in \mathcal{E}^0$ *and* $\nabla_{ad_e g} g \in \mathcal{E}^0$
3. $(MD3)$ $\nabla^2_{g,ad_e g} ad_e g - \nabla^2_{ad_e g,g} ad_e g \in \mathcal{E}^0$

Chapter 4

Results

Here, we consider an example: a simple mechanical system - the inertia wheel pendulum. The equations of motion are given by

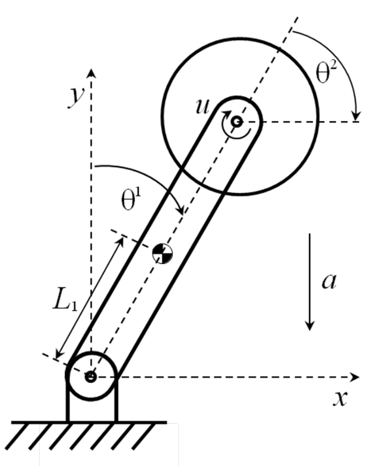


Figure 0.1: The inertia wheel pendulum

$$\begin{aligned} \mathfrak{m}_{11}\ddot{\theta}^1 + \mathfrak{m}_{12}\ddot{\theta}^2 + c^1 &= 0 \\ \mathfrak{m}_{21}\ddot{\theta}^1 + \mathfrak{m}_{22}\ddot{\theta}^2 &= u \end{aligned} \tag{0.1}$$

where

$$\begin{aligned} \mathfrak{m}_{11} &= m_d + J_2,\ \mathfrak{m}_{12} = \mathfrak{m}_{21} = \mathfrak{m}_{22} = J_2 \\ m_d &= L_1^2(m_1 + 4m_2) + J_1,\ m_0 = aL_1(m_1 + 2m_2) \\ c^1 &= -m_0 \sin\theta^1 \end{aligned}$$

Taking $(\theta^1, \theta^2) = (x_1, x_2)$ and correspondingly $(\dot{\theta}^1, \dot{\theta}^2) = (y_1, y_2)$, we get the following equations:

$$\begin{aligned} &\dot{x}_1 = y_1,\ \dot{x}_2 = y_2 \\ &\dot{y}_1 = e_1 + g_1 u,\ \dot{y}_2 = e_2 + g_2 u \end{aligned} \tag{0.2}$$

where

$$e_1 = \frac{m_0}{m_d}\sin x_1, \quad g_1 = -\frac{1}{m_d}$$
$$e_2 = -\frac{m_0}{m_d}\sin x_1, \quad g_2 = \frac{m_d + J_2}{m_d J_2}$$

4.1 MF-Linearization

We will verify $(MD1 - MD3)$ from Proposition 3.4.2, since the mechanical system here is a planar mechanical system.

1. First, we calculate:

$$\begin{aligned} \mathrm{ad}_e g &= 0 - \begin{pmatrix} \frac{m_0}{m_d}\cos x^1 & 0 \\ -\frac{m_0}{m_d}\cos x^1 & 0 \end{pmatrix} \begin{pmatrix} -\frac{1}{m_d} \\ \frac{m_d+J_2}{m_d J_2} \end{pmatrix} \\ &= \begin{pmatrix} \frac{m_0}{m_d^2}\cos x^1 \\ -\frac{m_0}{m_d^2}\cos x^1 \end{pmatrix} \end{aligned} \tag{1.1}$$

   It can be seen that g and $\mathrm{ad}_e g$ are independent (except at $x_1 = \pm\frac{\pi}{2}$). Thus, $MD1$ is satisfied.

2. To verify $MD2$,

$$\begin{aligned} \nabla_g g &= \left(\frac{\partial g_i}{\partial x_j} g_j + \Gamma^i_{jk} g_j g_k\right)\frac{\partial}{\partial x_i} = 0 \in \mathcal{E}^0 \\ \nabla_{\mathrm{ad}_e g} g &= 0 \in \mathcal{E}^0 \end{aligned} \tag{1.2}$$

   which is also verified.

3. Lastly, for $MD3$,

$$\nabla^2_{g,\mathrm{ad}_e g}\mathrm{ad}_e g = \nabla^2_{\mathrm{ad}_e g, g}\mathrm{ad}_e g = \begin{pmatrix} \frac{m_0^2}{m_d^5}\cos^2 x_1 \\ -\frac{m_0^2}{m_d^5}\cos^2 x_1 \end{pmatrix} \tag{1.3}$$

   and,

$$\begin{aligned} \nabla^2_{\mathrm{ad}_e g, g}\mathrm{ad}_e g &= \nabla_{\mathrm{ad}_e g}\nabla_g \mathrm{ad}_e g - \nabla_{\nabla_{\mathrm{ad}_e g} g}\mathrm{ad}_e g \\ &= \begin{pmatrix} \frac{m_0^2}{m_d^5}\cos^2 x_1 \\ -\frac{m_0^2}{m_d^5}\cos^2 x_1 \end{pmatrix} \end{aligned} \tag{1.4}$$

Thus, we have:

$$\nabla^2_{g,\mathrm{ad}_e g}\mathrm{ad}_e g - \nabla^2_{\mathrm{ad}_e g, g}\mathrm{ad}_e g = 0 \in \mathcal{E}^0 \tag{1.5}$$

Therefore, all the conditions $(MD1 - MD3)$ are satisfied, and the given system is *MF*-Linearizable.

We have the diffeomorphism $\Phi(x, y) = (\varphi(x), D\varphi(x)y)$, which is given by:

$$\begin{aligned}\tilde{x}_1 &= \frac{m_d + J_2}{J_2}x_1 + x_2,\ \tilde{x}_2 = \frac{m_0}{J_2}\sin x_1 \\ \tilde{y}_1 &= \frac{m_d + J_2}{J_2}y_1 + y_2,\ \tilde{y}_2 = \frac{m_0}{J_2}\cos x_1 y_1\end{aligned} \tag{1.6}$$

Taking $\tilde{\mathrm{x}} = \begin{pmatrix}\tilde{x}_1 & \tilde{x}_2 & \tilde{y}_1 & \tilde{y}_2\end{pmatrix}^T$, such that the linearized equations become:

$$\frac{d}{dt}\tilde{\mathrm{x}} = A\tilde{\mathrm{x}} + B\tilde{u} \tag{1.7}$$

Here, the matrices $A = \begin{pmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0\end{pmatrix}$, $B = \begin{pmatrix}0\\0\\0\\1\end{pmatrix}$ and $\tilde{u} = \psi(x, y, u)$ is the auxiliary control, such that:

$$\tilde{u} = -\frac{m_0}{J_2}\sin x_1 y_1^2 + \frac{m_0^2}{2m_d J_2}\sin 2x_1 - \frac{m_0}{m_d J_2}\cos x_1 u \tag{1.8}$$

4.2 Stabilization

We use the pole placement technique to obtain a control gain matrix K, such that $\tilde{u} = -K\tilde{x}$. Let us choose the poles of the closed-loop system to be:

$$\lambda = -10, -20, -30, -40 \tag{2.1}$$

Correspondingly, we obtain $K = \begin{bmatrix}240000 & 3500 & 50000 & 100\end{bmatrix}$

We denote $\mathrm{x} = \begin{bmatrix}x_1 & x_2 & y_1 & y_2\end{bmatrix}^T$ to get:

$$\frac{d}{dt}\mathrm{x} = (A - BK)\,\mathrm{x} \tag{2.2}$$

4.3 Discretization

We have the system in the form

$$\dot{\mathrm{x}} = (A - BK)\mathrm{x} = F(\mathrm{x})$$

Let h denote a (fixed) sampling time and $h' = \frac{h}{2}$. We utilize the symmetric discretization formulated in Section 1.1:

$$\begin{aligned}F(\mathrm{x}_k; h/2) &= F(\mathrm{x}_{k+1}; -h/2) \\ \mathrm{x}_k + h'(A - BK)\mathrm{x}_k &= \mathrm{x}_{k+1} - h'(A - BK)\mathrm{x}_{k+1} \\ \therefore \mathrm{x}_{k+1} &= (I - h'(A - BK))^{-1}(I + h'(A - BK))\mathrm{x}_k\end{aligned} \tag{3.1}$$

4.4 Simulations

We use the following parameters from [2] and [4]:

$$
\begin{aligned}
L_1 &= 0.063\ [m] \\
m_1 &= 0.02\ [kg] \\
m_2 &= 0.3\ [kg] \\
J_1 &= 47 \cdot 10^{-6}\ [kg \cdot m^2] \\
J_2 &= 32 \cdot 10^{-6}\ [kg \cdot m^2] \\
a &= 9.81\ [ms^{-2}] \\
m_0 &= 0.3832\ [kg \cdot m^2 s^{-2}] \\
m_d &= 49 \cdot 10^{-4}\ [kg \cdot m^2]
\end{aligned}
\tag{4.1}
$$

The comparison results between the proposed discretization scheme and ODE45 for the system, for a sampling time of $h = 0.01$, and initial conditions $\theta^1(0) = \frac{\pi}{4}, \theta^2(0) = \dot{\theta}^1(0) = \dot{\theta}^2(0) = 0$ are shown in Figure 4.1. The errors are plotted in Figs. 4.2, 4.3.

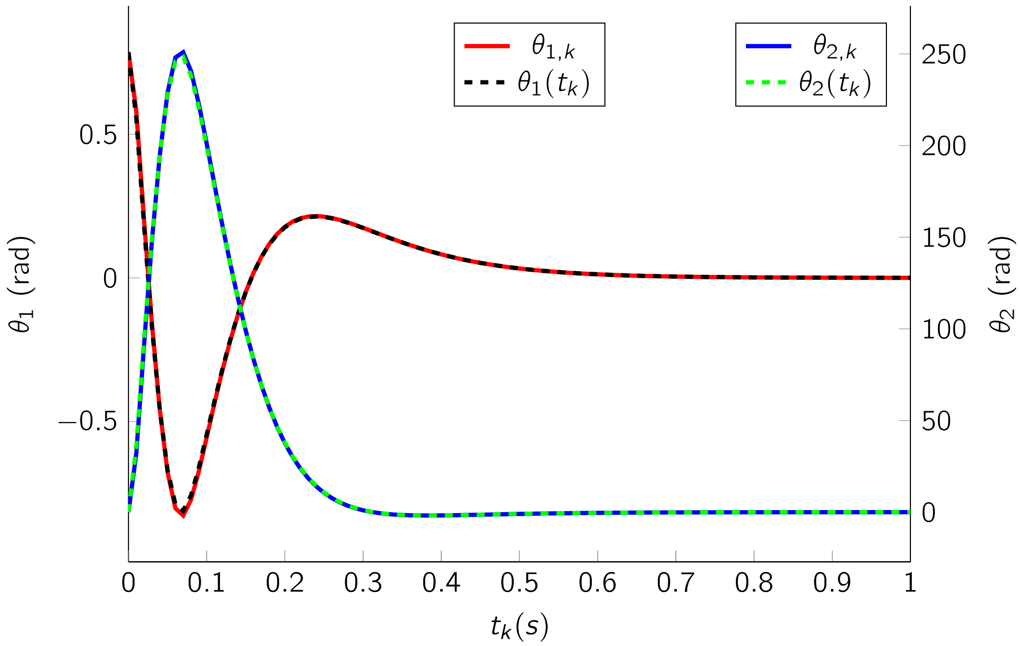


Figure 4.1: System states x_k for symmetric discretization plotted against exact discretization (ODE45) $x(t_k)$ for $t_k \in [0, 1]$

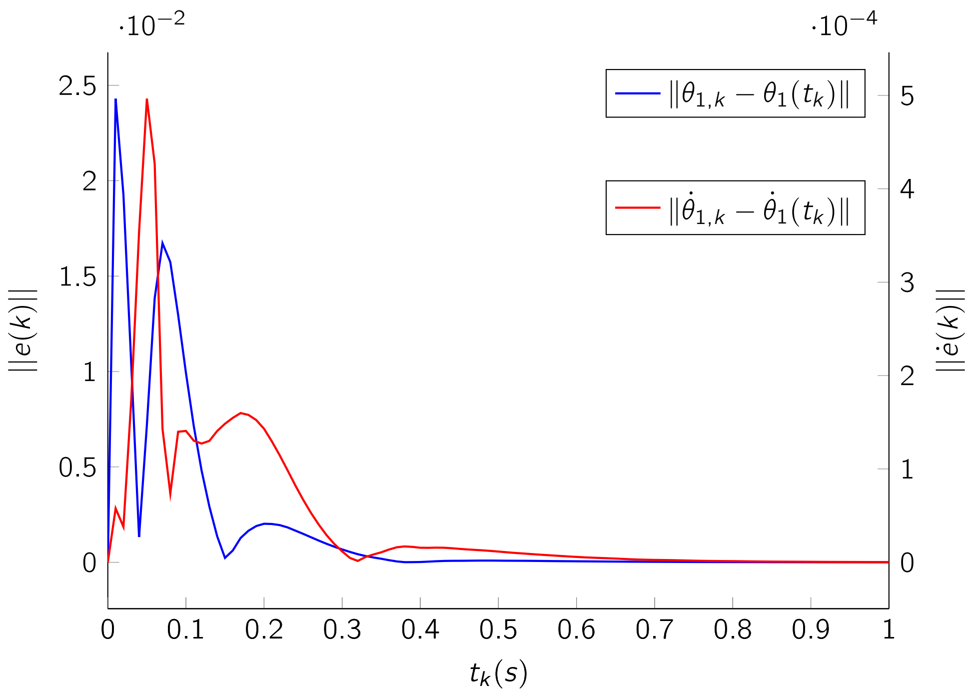


Figure 4.2: Magnitude of error norm for θ_1 and $\dot{\theta}_1$

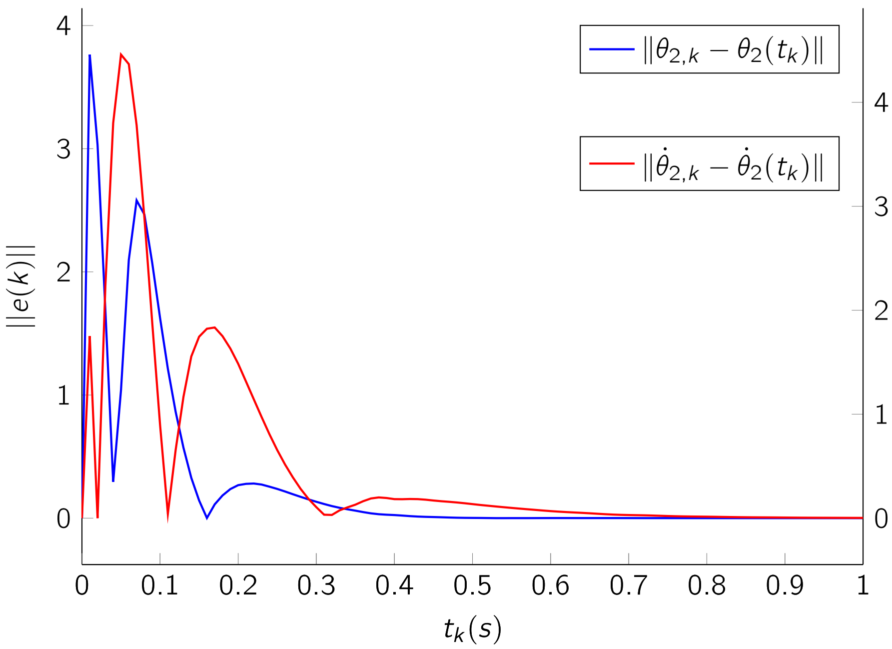


Figure 4.3: Magnitude of error norm for θ_2 and $\dot{\theta}_2$

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