Nonlinear Control using Coordinate-free and Euler Formulations: An Empirical Evaluation on a 3D Pendulum

Avinash Siravuru* Koushil Sreenath**

* Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15231, USA. (e-mail: avinashs@cmu.edu).
** Department of Mechanical Engineering, University of California, Berkeley, USA. (e-mail: koushils@berkeley.edu)

Abstract: Pendulum dynamics are widely utilized in robotics control literature to test and evaluate novel control design techniques. They exhibit many interesting features commonly seen in real-world nonlinear systems and yet they are simple enough for quick prototyping, further analysis, and benchmarking. In this work, we study the impact of a 3D pendulum’s orientation parametrization on stabilization performance. Mainly, we show that using a global or coordinate-free formulation for dynamics and control is not only singularity-free but also more input-efficient. We validate this empirically by running over 700 stabilization simulations across the full configuration space of a 3D pendulum and compare the performance of a geometric and a Euler-parametrized controller. We show that the geometric controller is able to leverage the inherent manifold curvature and flow along geodesics for efficient stabilization.

1. INTRODUCTION

Pendular systems are widely studied in the robotics and control community to discover and characterize nonlinear dynamical phenomena like symmetries, bifurcations, orbital stability, etc. (Lewis et al. (1992); Chaturvedi et al. (2011b); Lee et al. (2011)). The deeper understanding of these behaviors helps control theorists devise nonlinear control techniques for effective stabilization and tracking (Chung and Hauser (1995); Aström and Furuta (2000); Shiriaev et al. (1999)). The impact of pendular systems in robotics cannot be understated. Most complex robotic systems commonly apply pendular abstractions to model and control their dominant behaviors. For example, see pendulum-like models in robotic manipulation (Lefrançois and Gosselin (2010); Cunningham and Asada (2009); Zanotto et al. (2011)), inverted pendulum models in legged locomotion (Kajita et al. (2001); Chevallereau et al. (2018); Poulakakis and Grizzle (2009)), and multi-link pendular models in brachiation (Saito et al. (1994); Farzan et al. (2019)). To date, multi-link pendula, remain the best nonlinear system models for benchmarking performance of new control algorithms on typical real-world challenges like underactuation, model uncertainty, stochasticity, etc.

Traditionally, nonlinear control design techniques used for stabilization or swinging up of a 3D or spherical pendulum (a.k.a 3D pendulum that cannot yaw) used Euler angles to define the pendulum configuration (Shiriaev et al. (1999); Liu et al. (2005); Aguilar-Ibanez et al. (2006)). However, more recently, coordinate-free formulations have been proposed to define pendulum configuration and corresponding dynamical models (Chaturvedi et al. (2011b); Lee et al. (2011); Bittner and Sreenath (2016)) and suitable control laws (Chaturvedi et al. (2011a); Lee (2011)) have been devised. These globally-defined dynamical formulations are singularity-free, i.e., they are devoid of kinematic singularities like gimbal-lock seen in locally-defined formulations like Euler angles (For example, the $ZXY$-ordering Euler-angles ($[\phi \theta \psi]^T$) exhibit a singularity when $\phi = \pi/2$).

The singularity-free property of global formulations has implications in control design, particularly, recovery from large angle disturbances is possible and the controllers can be designed to be almost-globally attractive (as opposed to weaker local attractivity properties of Euler-based control designs). A new sub-field in nonlinear control, called geometric control has emerged that exploits these control laws and its been heavily applied in UAV literature, see Lee et al. (2013); Sreenath and Kumar (2013); Lee (2017); Mueller (2018) and more recently in legged locomotion, see Sreenath and Sanyal (2015); Siravuru et al. (2018); Ding et al. (2019).

Prior literature on geometric control has primarily focused on providing mathematical rigor and experimental validation to geometric control, specifically the almost-global attractivity property and the freedom from singularities. While these two properties are more meaningful for developing UAV maneuvers to quickly recover from large disturbances, for legged robots and other systems, the use of geometric control needs further motivation. Large angle recoveries are uncommon (restricted to acrobatic motions) and may be impractical during regular locomotion tasks like walking, running, etc. due to limited control authority, finite time (to impact) and narrow region-of-attraction.

In this work, we demonstrate the other advantages of geometric control that make it an appealing choice even for legged locomotion. Through a comprehensive empirical evaluation of 3D Pendulum stabilization to its hanging equilibrium position, we show that geometric control is more input-efficient than traditional Euler angles-based
nonlinear control. This fact purely stems from the exploitation of inherent curvature in the $SO(3)$ manifold space that is thrown away when an Euler-parameterization is used. The feedback laws built directly on $SO(3)$ use the geodesics for error correction and are therefore more efficient. As both nonlinear controllers are equivalent to the first order, the efficiency of the geometric controller is more pronounced for larger error recovery.

The rest of this paper is organized as follows. In Section 2, we summarize the 3D pendulum dynamical model using both Euler and geometric formulations. Next, in Section 3, we define feedback linearization control laws for both the Euler and geometric formulations and compare the error metric choices of the two formulations. In Section 4, we comprehensively evaluate the performance of the two models, and finally, we provide concluding remarks in Section 5.

2. MODEL DEFINITIONS

To define the mathematical model of the 3D pendulum, we first need to define a stationary fixed frame (inertial frame) about which the pendulum configuration is measured. Denote this frame as $\{I\}$ and fix it at the origin, which is also the pivot for the pendulum. Second, we attach a moving frame (body frame), denoted as $\{B\}$, to the center-of-mass (CoM) of the pendulum. Having defined the frames, the next step is to choose a suitable parametrization to represent a 3D rotation - this translates to estimating the orientation of $\{B\}$ w.r.t. $\{I\}$, as shown in Fig. 1. In this work, we use two methods, 1) Euler-based (ZYX ordering): $q \in \mathbb{R}^3$, and 2) Geometric: $R \in SO(3)$. Other model parameters used for modeling and control design are defined and summarized in Table 1.

2.1 3D Pendulum Dynamics

Pendulum dynamics using both Euler and $SO(3)$ formulations can be compactly expressed as,

\begin{align}
D_e(q) \ddot{q} + H_e(q, \dot{q}) \dot{q} &= B_e u_e, \\
SO(3): \quad D_s(R) \ddot{\Omega} + H_s(R, \Omega) \dot{\Omega} &= B_s u_s,
\end{align}

where $q = [\phi \ \theta \ \psi]^T$, $\dot{q} = [\dot{\phi} \ \dot{\theta} \ \dot{\psi}]^T$, and $u_e \in \mathbb{R}^3$.

For the derivation of these equations, see Lee et al. (2017) and Chatuvedi et al. (2011b). The hat map used in equation 4, and its inverse - the $vee$ map - are defined in Table 1. Note that the dynamics cannot be directly compared and we need to define suitable mapping between the Euler angles, rates and inputs to their counterparts in $SO(3)$.

2.2 Transfer Maps

Using the ZXY ordering of Euler angles, we define $R(q): \mathbb{R}^3 \rightarrow SO(3)$ whose expression is given as,

\begin{equation}
R(q) = \begin{pmatrix}
\cos(\phi) \cos(\psi) - \sin(\phi) \sin(\theta) & \cos(\phi) \sin(\psi) + \sin(\phi) \cos(\theta) & \sin(\phi) \\
-\sin(\phi) \cos(\psi) - \cos(\phi) \sin(\theta) & \sin(\phi) \sin(\psi) - \cos(\phi) \cos(\theta) & \cos(\phi) \\
\sin(\theta) & -\cos(\theta) & 0
\end{pmatrix},
\end{equation}

s.t. $R = R(q)$. Here, we compactly represent $\cos(\alpha)$ and $\sin(\alpha)$ as $c\alpha$ and $s\alpha$, respectively, and $\alpha$ is a placeholder for any Euler angle in $q$.

Next, we define $T_q(q): \mathbb{R}^3 \rightarrow \mathbb{R}^{3 \times 3}$ to convert Euler rates ($\dot{q}$) to angular velocities ($\Omega$) as shown below:

\begin{equation}
T_q(q) = \begin{pmatrix}
0 & -c\phi & s\phi \\
0 & c\phi & s\phi \\
s\theta & 0 & 0
\end{pmatrix}, \quad \text{s.t. } \Omega = T_q(q) \dot{q}.
\end{equation}

Finally, to convert Euler input ($u_e$) to $SO(3)$ input ($u_s$), we define $T_u(q, R): \mathbb{R}^3 \times SO(3) \rightarrow \mathbb{R}^{3 \times 3}$ as,

\begin{equation}
T_u(q, R) = (D_e^{-1} B_e)^{-1} T_q(q)(D_e^{-1} B_e),
\end{equation}

s.t. $u_s = T_u(q, R) u_e$.

$T_q$ Derivation: We first define $R_w(\alpha): \mathbb{R} \rightarrow SO(3)$ as a mapping from an Euler angle $\alpha$ to its corresponding axis-specific rotation matrix $R_w$. Following the $ZXY$
Euler sequencing, we have $\alpha \in [\psi \phi \theta]^T$ representing a rotation about an axis denoted by $w_i \in [Z X Y]^T$ and whose unit vector is denoted by $e_i$. Accordingly, we have $R_{w_i} = R_{w_i} \hat{e}_i$. Using this notation, we express $R$ as a product of its individual axis-wise rotation elements $R_z(\psi)$, $R_y(\phi)$, and $R_y(\theta)$. We can then compute its first derivative, $\dot{R}$, as a function of Euler angles $q$ and their Euler rates $\dot{q}$, as shown below:

$$R = R_z R_x R_y,$$

$$\Rightarrow \dot{R} = \dot{R}_z R_x R_y + R_z \dot{R}_x R_y + R_z R_x \dot{R}_y,$$

$$= R_z \dot{\psi} e_3 R_x R_y + R_x \dot{\phi} e_1 R_y + R_z R_x \dot{\theta} e_2.$$

From equation (3), we know that $\Omega = (R^T \dot{R})^\gamma$. Therefore,

$$\dot{\Omega} = R_y^T R_z \dot{R}_x R_y + R_y^T R_z \dot{R}_x R_y + R_y^T R_z \dot{R}_x e_1 R_y +$$

$$R_y^T R_z \dot{R}_x R_y + R_y^T R_z \dot{R}_x e_1 R_y + \dot{\theta} e_2,$$

$$= R_y^T R_z \dot{\phi} e_3 + R_y^T \dot{\phi} e_3 R_y + \dot{\theta} e_2.$$

Finally, we apply a $\psi e$ map on both sides to get,

$$\Omega = [R_y^T e_1 \, e_2 \, R_y^T e_3] \begin{pmatrix} \phi \\ \dot{\phi} \\ \dot{\psi} \end{pmatrix},$$

$$\Rightarrow \mathcal{T}_q(q) = [R_y^T e_1 \, e_2 \, R_y^T e_3] = \begin{pmatrix} c\theta & 0 & -c\phi \sin \theta \\ 0 & 1 & \sin \phi \cos \theta \\ c\phi & 0 & c\phi \sin \theta \end{pmatrix}.$$

**$T_u$ Derivation:** We can obtain $T_u$ by taking the time derivative of equation (6), then substituting the dynamics from equations (12) and (13) for $\ddot{q}$ and $\dot{\Omega}$. Finally, we equate the input vector fields on both sides to finish the derivation. In particular,

$$\Omega = \mathcal{T}_q(q) \dot{q},$$

$$\Rightarrow \dot{\Omega} = \dot{T}_q \dot{q} + T_q \ddot{q},$$

$$= A_u \dot{q} + B_u \ddot{q} = T_q \ddot{q} - T_q D_x^{-1} H_x + T_q (D_x^{-1} B_e u_e).$$

Note that, the equality in equation (9) hold for all $u_e$ and $u_s$. Setting $u_e = u_s = 0$ results in $A_e = A_s$. Eliminating, $A_e$ and $A_s$, we can define,

$$u_s = (D_x^{-1} B_e)^{-1} 1 \mathcal{T}_q(D_x^{-1} B_e) u_e,$$

$$\Rightarrow T_u = (D_x^{-1} B_e)^{-1} 1 \mathcal{T}_q(D_x^{-1} B_e).$$

Using these transfer maps it is easy to compare the Euler and geometric control laws which are going to be defined in the next section.

### 2.3 Pendulum State Sampling:

In the following sections, we empirically evaluate kinematic and dynamical defects like singularities, control design attributes like error metrics, input profiles, etc. for both $SO(3)$ and Euler models for a wide range of pendulum configurations/states. The main emphasis of this work is to use this comprehensive empirical evaluation to highlight the benefits of geometric control and complement mathematically rich previous works.

The states are sampled from a $[-\pi, \pi]$ range of $\phi, \theta$, and $\psi$ values with a resolution of $\pi/4$. The corresponding $SO(3)$ states can be obtained using transfer map $R$. For dynamic and kinematic studies, these configurations can be treated as a potential intermediate state in the pendulum motion trajectory. For control studies, they are used as initial conditions from which the pendulum is stabilized to its hanging equilibrium position. Some of these state samples are shown in Fig. 2 along-with the sample numbers to be used in plots that follow.

Note that both $\mathcal{T}_q$ and $D_q$ lose rank when $\phi = \pi/2$. This is the singularity issue that plagues Euler parametrization. Singular states are littered all over the configuration space, as shown in Fig. 3, making large disturbance recovery challenging using Euler parametrization.
3. CONTROL LAWS

Error Metrics: Before designing controllers and testing their performance, it is worth defining suitable error metrics for the Euclidean and $\mathbb{SO}(3)$ spaces to measure error growth between desired and actual pendulum states as they spread apart. This metric is directly proportional to the control expense involved. This helps us visualize a priori configurations that require greater control effort.

Euler: Define non-negative function $\Psi_e: \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R}$ as,

$$
\Psi_e = \frac{1}{2} \sqrt{(q - q_d)^T(q - q_d)}.
$$

$\mathbb{SO}(3)$: Define $\Psi_s: \mathbb{SO}(3) \times \mathbb{SO}(3) \rightarrow \mathbb{R}$ as,

$$
\Psi_s = \frac{1}{2} tr[I - R_d^T R].
$$

Assuming the hanging equilibrium configuration (i.e. $q_d = [0 \ 0 \ 0]^T$ or $R_d = I$) is desired, we pick $q$ from all the states defined in the earlier section (Fig. 2) and plot $\Psi_e$ in Fig. 4 and $\Psi_s$ in Fig. 5.

On the $\mathbb{SO}(3)$ manifold, configurations where either one or two Euler angles $\approx \pi$ (antipodal configurations) are the farthest from $q_d$. These configurations are depicted by the cross-type bands around face centers on the samples cube in Fig. 5. On the other hand, note that the highest error points in Fig. 4 pertain to instances where all the three Euler angles $\approx \pi$ (depicted by the edges of the samples cube). This is non-uniform as these points are actually very close to the desired configuration on the $\mathbb{SO}(3)$ manifold and should require minimal effort to reach $q_d$. Even before evaluating the controller performance, the error metrics clearly highlight the inefficiencies induced by an Euler-based controller design.

Control Design: In this work, we choose Feedback Linearization (FL) for pendulum stabilization. We begin by rewriting equations (1) and (2) in the control-affine form as,

$$
\dot{x}_e = f_e(x_e) + g_e(x_e)u_e,
$$

$$
\dot{x}_s = f_s(x_s) + g_s(x_s)u_s,
$$

where $x_e = [q \ q_d]^T$ and $x_s = [R \ \Omega]^T$. Note that $x_s$ is a set. The Feedback Linearization schemes for both models are summarized below:

Euler: For the Euler case, it is fairly straightforward to derive an appropriate feedback linearizing policy by defining a suitable output as $y_e = h_e(q) = q - q_d$. Here, $q_d(t)$ can be time-varying and the control problem transitions to tracking from regulation. The output is relative degree 2. The control goal is to drive the output $y_e \rightarrow 0$, i.e.,

$$
y_e := h_e(q) = q - q_d(t) \rightarrow 0,
$$

$$
\Rightarrow y_e = L_{d_h} y_e = \dot{q} - \dot{q}_d(t),
$$

$$
\Rightarrow \dot{y}_e = L_{d_h}^{\frac{c}{2}} h_e + (L_{d_h} L_{d_h}) u_e - \dot{q}_d(t) = \ddot{q} - \dot{q}_d(t),
$$

where, $L_{d_h} h_e$ is the lie derivative and $L_{d_h} h_e(q) = \frac{\partial h_e}{\partial q} f$.

Now let define suitable feedforward and feedback terms,

$$
u_{e f} := -(L_{d_h} L_{d_h})^{-1}(L_{d_h}^{\frac{c}{2}} h_e),
$$

$$
u_{e b} := -(L_{d_h} L_{d_h})^{-1}(K_p y_e + K_d y_e).
$$

Applying $u_e := u_{e f} + u_{e b}$ in equation (16) results in a closed-loop linear system,

$$
y_e + K_d y_e + K_p y_e = 0.
$$

$\mathbb{SO}(3)$: Feedback Linearization for $\mathbb{SO}(3)$ dynamics is non-trivial. Here we use geometric PD error functions previously introduced in Lee (2012, 2011) and presented in (20). Here $c_R$ is the configuration error akin to angle errors in the Euclidean space. Similarly, $c_\Omega$ is angular velocity error. The extra term $(R_d^T R_d)$ in $c_R$ is called a transport map. Since the tangent spaces on $\mathbb{SO}(3)$ change with configuration ($\Omega \in T_R \mathbb{SO}(3)$ & $\Omega \in T_R \mathbb{SO}(3)$), the transport map helps project desired angular velocities onto the tangent space at the current configuration ($T_R \mathbb{SO}(3) \rightarrow T_R \mathbb{SO}(3)$) for correct comparison.

Similar to equation (19), we desire an exponentially stable closed-loop error dynamics of the form

$$
\dot{c}_\Omega + K_4 c_\Omega + K_p c_R = 0.
$$

Using a non-negative constant $c$, we define a candidate Lyapunov function $V$ as
\[ V = \frac{1}{2} e^T J e + J K_p \Psi_s (R, R_d) + c e^T R e, \]  
where \( \Psi_s \) is an error metric on \( SO(3) \times SO(3) \) defined earlier in (11), and for a given \( R_d, \Psi_s \leq 2 \). Further, the time derivative of \( \Psi_s \) is \( \dot{\Psi_s} = e^T R e \) (for proof, see Lee et al. (2010)). Using this we can compute the time derivative of \( V \) as,

\[ \dot{V} = e^T J e + J K_p e e^T R e + c e^T R e, \]  
(23)

Using equations (2), (20c), and (20d) and defining \( u_s \) as

\[ u_s = \tilde{\Omega} J \Omega + mg \tilde{\hat{R}}^T e_3 - J \tilde{\Omega} R^T R_d \Omega_d + J R^T R_d \Omega_d \]

\[ \left( -JK_p e + JK_d e \right) \right], \]  
(24)

we get,

\[ \dot{V} = -(JK_d - c \Upsilon) ||e||^2 - c K_p ||e||^2 - c K_d e^T R e, \]  
(25)

Since \( \Upsilon \) in (20c) satisfies \( ||\Upsilon|| \leq 1 \), this is bounded by

\[ \dot{V} \leq -\eta^2 W \eta, \]  
(26)

where \( \eta = ||e||, ||e\Omega|| \), and the matrix \( W \in \mathbb{R}^{2 \times 2} \) is

\[ W = \begin{bmatrix} c K_p & -c K_d \\ -c K_d & \lambda_{M(J)K_d - c} \end{bmatrix}, \]  
(27)

with \( c, K_p, \) and \( K_d \) chosen such that \( W \) is positive definite. Finally, \( \lambda_{M(J)} \) denotes the largest eigen value of \( J \). Thus, using \( V \) and \( u_s \) defined in (22) and (24), we can convert error dynamics in (20d) to the desired closed-loop exponentially stable dynamics in (21). A more detailed convergence proof can be derived following the process shown in Lee et al. (2010) (Appendix B).

4. RESULTS AND DISCUSSION

The control objective in this study is to stabilize the 3D pendulum to its hanging equilibrium position. Euler rates in \( \dot{\theta}_d \) are randomized for each trial with a max of 4 rad/s per state and \( \Omega_d \) is determined using the \( \tilde{T}_q \) mapping. The initial condition of the pendulum could be any state \( m \) w.r.t body-frame as

\[ \dot{\theta}_d \]

controller for the Euler dynamics and a geometric controller for the \( SO(3) \) dynamics and logged key performance metrics like input integral over time, power integral over time, max input, and max power.

**How to compare the two?** After applying the two controllers and logging performance data across a range of initial conditions, we compare both of them in the Euler-space. We use the maps defined in Sec. 2.2 to map \( R(t), \Omega(t), \) and \( u_s(t) \) to \( \tilde{q}(t), \tilde{\Omega}(t), \) and \( \tilde{u}_e, \) respectively. Therefore,

\[ \tilde{q} = R^{-1}(R), \tilde{\Omega} = \tilde{T}_q^{-1}(\Omega), \tilde{u}_e = \tilde{T}_u^{-1}(u_s). \]  
(28)

**Geometric Control is more efficient:** Having logged both \( u_e \) and \( \tilde{u}_e, \) we plot joint-wise integrals for each experiment in Fig. 6. Note that, \( \tilde{u}_e \) is particularly efficient compared to \( u_s. \) The existence of singularity in the \( \phi \) direction impacts all trajectories in the Euler model with large \( \phi \) errors.

Next, we evaluate metrics for full attitude control performance. We show normed input integral and power integral plots in Fig. 7 and max input and max power plots in Fig. 8. Note that both over time and in magnitude the geometric controllers are consistently more efficient. Also, the max input and power values for Euler controller are particularly high in some cases, mainly while crossing the singularity configuration where the numerical integrator applies arbitrarily large inputs. However, on a real system with strict input saturation this difference would be less severe.

5. CONCLUSIONS AND FUTURE WORK

In this work, we presented two formulations for modeling and control of a 3D pendulum - one is Euler-parameterized and the other is coordinate-free geometric formulation in the \( SO(3) \) manifold space. Through comprehensive empirical evaluation, we demonstrate that geometric control is generally more input efficient than the more conventional Euler-parametrized nonlinear control, not just for large error recovery as was mainly shown so far.
We hope that this study assists in a wider adoption of coordinate-free modeling and control design beyond aerial robotics. As a part of future work, we wish to extend our empirical performance assessment studies to underactuated double pendular systems popularly studied in the legged and brachiating robot communities. Further, we also plan to develop trajectory optimization routines to discover optimal motion plans directly in the $\text{SO}(3)$ space.

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