Robust control system design for self-standable motorcycle

Susumu HARA*, Koki NAKAGAMI*, Kikuko MIYATA*, Mitsuo TSUCHIYA** and Eiichirou TSUJII**

*Department of Aerospace Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya-shi, Aichi 464-8603, Japan
E-mail: haras@nuae.nagoya-u.ac.jp

**Yamaha Motor Co., Ltd.
2500 Singai, Iwata-shi, Shizuoka 438-8501, Japan

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Abstract
This study discusses the verification of the control system for realizing autonomous standing up from the parking mode of a novel motorcycle with a self-stabilizing mechanism, named “MOTOROiD,” and ensuring its stability on low-speed driving. MOTOROiD has a novel rotary axis that can vary the position of the total center of gravity, referred to as the active mass center control system (AMCES). In the previous study, the authors derived a mathematical model using Lagrange’s equation of motion, designed a control system for standing up from the parking mode, and ensured the motorcycle’s stability by using a two-degree-of-freedom control system based on the established model. However, the robustness of the proposed system was not fully verified. The previous study only verified the robustness of the mass variation with a numerical simulation example. Therefore, this study demonstrates the effectiveness of the proposed control system using several numerical simulations with variations in the system parameters. The simulation conditions are set by considering the characteristics of MOTOROiD in realistic situations related to a parked motorcycle. We consider three cases: (i) MOTOROiD is parked on a sloped ground, (ii) the angle of inclination at parking mode is not as assumed, and (iii) MOTOROiD is influenced by Coulomb friction. We set the simulation parameters based on these cases. Consequently, we confirm that MOTOROiD can stand up autonomously under all these conditions, thereby demonstrating the practicality of the proposed control system.

Keywords: Robust control, Optimal control, Double pendulum, Two-degree-of-freedom control, Standing up, Motorcycle

1. Introduction

Recently, extensive studies have focused on realizing novel mobility technologies, with special consideration for the aging society. The primary aim of these studies is to establish autonomous driving technology (ADT). Mainly, the objects of ADT are four-wheel motor vehicles, and new technologies are investigated from various viewpoints such as vehicle development and infrastructure improvements. However, ADT for motorcycles has received scant attention. In Japan, the motorcycle mortality rate is approximately quadruple that of four-wheel motor vehicles. Therefore, the design of autonomous motorcycles has become imperative. Furthermore, among the various operation conditions, the low-speed driving mode is the most unstable mode for motorcycles. Thus, autonomously standing up from the parking mode and stability for low-speed driving are very important subjects that should be explored under ADT. To fill this gap, some conventional studies have explored the incorporation of gyro mechanisms (Ouchi, et al., 2015) or counterweights and guide rail in motorcycles (Satoh and Namerikawa, 2006). However, these additional mechanisms often make the motorcycles bigger and heavier. In 2017, Yamaha Motor Co., Ltd. released MOTOROiD, a motorcycle with self-stabilizing mechanism (Tsuchiya, et al., 2018) (Fig. 1). MOTOROiD has a novel rotary axis, active mass center control system, (AMCES, Fig. 2), and can vary the position of the total center of gravity. For this mechanism, Yamaha designed a control system using the combination of a minor loop proportional–integral–derivative (PID)
controller and an optimal adaptive-type linear–quadratic regulator (LQR); the experimental trial-and-error implementation demonstrates that control was achieved (Tsuchiya, et al., 2018). However, the system design is based on limited experiments, and the effectiveness of the designed control system was only verified for the experimental system. Therefore, the robustness of the control system against parameter uncertainties was not ascertained. For ensuring motorcycle safety, it is necessary to design a more systematized control system based on a mathematical model. To meet this requirement, the authors performed the mathematical modeling of MOTOROiD, and designed a control system based on the obtained model in a previous study (Hara, et al., 2019). In the study, the effectiveness of the control system in relation to parameter uncertainties, specifically system weight variation, is verified. However, because the study only considered the case of weight variation, it does not sufficiently demonstrate the robustness of the proposed control method. With regard to the practical use environment, there are parameter variations besides weight variations; thus, additional verifications are necessary to demonstrate the robustness of the proposed design. Thus, we focus on situations where the payload is loaded, the attitude at the parked mode is not as assumed, or the Coulomb friction influences the input. The proposed control system is not practical if MOTOROiD cannot stand up under these conditions at the minimum. Therefore, we set specific conditions, other than weight variations, and perform numerical simulation. From the results, we evaluate the practicability of the proposed control system.

2. MOTOROiD

MOTOROiD (Fig. 1) is a proof-of-concept experimental electric motorcycle aimed at new forms of personal mobility (Tsuchiya, et al., 2018). Its center of gravity is adjusted with the sensor’s status measurement that enables it to get off its kickstand and achieve the upright position unassisted. In this study, the settling state using the kickstand is defined as the parked mode.

AMCES (Fig. 2) controls and stabilizes the chassis of two-wheeled electric motorcycles electronically. By actively controlling the chassis itself, the optimal state of operation of the vehicle can be constantly maintained, allowing the machine to keep itself upright when standing still or moving forward. Attaining this stable state is the preoccupation of this study. Controlling the attitude of the machine is achieved by rotating parts of the machine, such as the battery, swingarm, and rear wheel, around the AMCES axis that runs through the center of the vehicle to control its center of gravity. The AMCES axis also serves as a joint connecting the red part (Q1) and blue part (Q2), as shown in Fig. 2. During rotation, the battery either moves right or left, acting as a counterweight that enables the machine to maintain balance and remain upright at standstill. The intersection point of the AMCES axis and the ground is also the grounding point of the rear wheel. Therefore, the grounding point of the rear wheel is always fixed, even when the AMCES axis is rotated. The inner frame unit area rotates around the AMCES axis via electronic control.

3. Modeling

This section discusses the mathematical modeling of MOTOROiD. The authors have already provided the overview of the Lagrange’s equations of motion-based modeling method (Hara, et al., 2019). In this section, we provide
the summary of the modeling method. As established in the previous study, the most important part of modeling is the AMCES axis. Other complex elements are not necessary to simulate the rough response in the self-stabilizing control from the parked mode. Therefore, the equation of motion for MOTOROiD is derived by introducing the following simplification to the system. The system is divided into two structures (Fig. 3): a front-wheel part and a rear-wheel part. The AMCES shaft connects these bodies as a rotary joint. This mechanism can be regarded as a double pendulum from the front view of the main body. In addition, it is considered a kind of acrobot, because only the connection portion of the body equips the actuator (Spong, 1995).

\[ \text{Fig. 3 Schematic figure of AMCES-axis} \]

Having introduced the absolute coordinate system, the system is assumed to be on a flat ground. The x-axis is defined along the axis connecting the grounding points of the two tires. The z-axis is defined to be normal to the x-axis in an anti-gravity direction. The y-axis is defined to be normal to the other axes based on the right-hand coordinate system definition. Here, the system differs from the typical acrobot, because the directions of the x-axis and AMCES axis are not similar. Therefore, the equation of the motion cannot be simply described on the two-dimensional plane, and specialized modeling is required. The front-wheel part of the motorcycle is defined as Q1, and the rear part is defined as Q2. Let \( q_1 \) be the slant angle of Q1 in the standing state, and \( q_2 \) be the angle between Q1 and Q2 due to the rotation of the AMCES axis.

Lagrange’s equation of motion is a well-known modeling method based on Lagrangian mechanics (Taylor, 2005). Lagrange’s equation of motion is derived by individually calculating the kinetic energy and potential energy. In addition, the energies of Q1 and Q2 can be calculated independently. The energy of the MOTOROiD as a whole is the sum of the kinetic and potential energy of the individual components. This subsection mainly focuses on the important elements to obtain the kinetic energies of Q1 and Q2.

First, the kinetic energy of Q1 is discussed. The origin of the coordinate system for Q1 is considered to be the ground point of the rear wheel. The Q1 coordinate system becomes the same as the absolute coordinate system when Q1 is perpendicular to the ground. The position vector of the center of gravity on Q1, \( r'_{G1} \), in the Q1 coordinate system always becomes:

\[ r'_{G1} = \begin{pmatrix} -l_1 \\ 0 \\ l_2 \end{pmatrix}. \]  

\[ (1) \]

The x-axis of the Q1 coordinate system and the absolute coordinate system are always equal. Let \( r_{G1} \) be the position vector of the center of gravity on Q1 based on the absolute coordinate system. Tilting Q1 to the angle \( q_1 \) from the perpendicular state to the ground, \( r_{G1} \) is expressed using the rotation matrix \( A^{0G1} \) with the Euler angle as follows:

\[ r_{G1} = A^{0G1} r'_{G1}, \]  

\[ (2) \]

\[ A^{0G1} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos q_1 & -\sin q_1 \\ 0 & \sin q_1 & \cos q_1 \end{pmatrix}. \]  

\[ (3) \]
Let $\dot{r}_{G1}$ be the velocity vector of the center of gravity on Q1 based on the absolute coordinate system. $\dot{r}_{G1}$ is expressed thus:

$$\dot{r}_{G1} = \frac{d}{dt} r_{G1}. \quad (4)$$

The Q2 kinetic energy is discussed in the Q2 coordinate system. The origin of the coordinate system for Q2 is set to $C_2$, as expressed in Fig. 3. $C_2$ is the intersection of the AMCES axis and the axis that is normal to the AMCES axis passing the center of gravity of Q2. The x-axis is defined along the direction to the grounding point of the rear wheel. The z-axis is defined along the direction connecting the center of gravity of Q2 and AMCES axis. The y-axis is defined to be normal to the other axis according to the definition of the right-hand coordinate system. When the angle $q_2$ of the AMCES axis is 0, the y-axis of the Q1 and Q2 coordinate systems become similar for the arbitrary $q_1$. Then, the Q1 and Q2 coordinate systems can be connected by the rotation of $a_2$ around the y-axis.

In the Q2 coordinate system, the coordinate $r'_{G2}$ of the center of gravity of Q2 always becomes:

$$r'_{G2} = \begin{pmatrix} 0 \\ 0 \\ -l_4 \end{pmatrix}. \quad (5)$$

Let $r_{G2}$ be the position vector of the center of gravity of Q2 as seen from the absolute coordinate system. Because $q_2$ expresses the angle of Q1 and Q2, $r_{G2}$ cannot be derived based on $q_2$ alone. Let $r'_{G2}$ be the position vector of the center of gravity of Q2 as seen from the Q1 coordinate system. At first, we express $r'_{G2}$ using the rotation matrix and the translation of the coordinates. Then, we obtain $r_{G2}$ using the rotation matrix $A^{OG1}$. Here, $r'_{G2}$ can be expressed as:

$$r'_{G2} = A^{G1G2}r_{G2}' + \begin{pmatrix} -l_4 \cos a_2 \\ 0 \\ l_4 \sin a_2 \end{pmatrix}. \quad (6)
$$

$$A^{G1G2} = \begin{pmatrix} \cos a_2 & 0 & \sin a_2 \\ 0 & 1 & 0 \\ -\sin a_2 & 0 & \cos a_2 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos q_2 & -\sin q_2 \\ 0 & \sin q_2 & \cos q_2 \end{pmatrix}. \quad (7)$$

From the relationship between the Q1 coordinate system and the absolute coordinate system, $r_{G2}$ is represented thus:

$$r_{G2} = A^{OG1}r'_{G2}. \quad (8)$$

As in Eq. (4), the velocity vector $\dot{r}_{G2}$ of the center of gravity of Q2 in the absolute coordinate system is:

$$\dot{r}_{G2} = \frac{d}{dt} r_{G2}. \quad (9)$$

Through these analyses, we can obtain the kinetic energy and potential energy caused by the parallel movement of the center of gravity.

Next, we discuss the kinetic energy of the rotation around the center of gravity. The angular velocity vector $\omega'_1$ of Q1 in the Q1 coordinate system becomes:

$$\omega'_1 = \begin{pmatrix} \dot{q}_1 \\ 0 \\ 0 \end{pmatrix}. \quad (10)$$

The angular velocity vector $\omega'_2$ of Q2 in the Q2 coordinate system includes not only the rotational speed of the AMCES axis but also the rotational speed of Q1. Therefore, $\omega'_2$ becomes:

$$\omega'_2 = (A^{G1G2})^T \omega'_1 + \begin{pmatrix} \dot{q}_2 \\ 0 \\ 0 \end{pmatrix}. \quad (11)$$

The inertia tensor seen from the object coordinate system is always constant. Let $I_1$ and $I_2$ be the inertia tensor of Q1 and Q2 in the absolute coordinate system, respectively, under the condition that $q_1$ and $q_2$ are 0. Let $I'_1$ and $I'_2$ be the inertia tensor as seen from the Q1 and Q2 coordinate systems. $I'_1$ and $I'_2$ are expressed with $I_1$ and $I_2$ thus:

$$I'_1 = I_1, \quad (12)$$

$$I'_2 = |(A^{G1G2})^T I_2 A^{G1G2}|_{q_2=0}. \quad (13)$$
With these relationships, the kinetic energies of Q1 and Q2 are obtained as \((1/2)m_1|\dot{r}_{G1}|^2 + (1/2)\omega_1^2T_1\omega_1^2\) and \((1/2)m_2|\dot{r}_{G2}|^2 + (1/2)\omega_2^2T_2\omega_2^2\), respectively. Here, \(m_1\) and \(m_2\) are the masses of Q1 and Q2, respectively. We can calculate the Lagrangian equation of motion using these kinetic energies and potential energies, depending on the gravity, and partially differentiate with the angle and angular velocity (Taylor, 2005). The Lagrangian \(L\) is expressed as:

\[
L = T - U
\]

where \(T\) is the kinetic energy, and \(U\) is the potential energy of the entire MOTOROiD. Lagrange’s equation of motion expressed as:

\[
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_1}\right) - \frac{\partial L}{\partial q_1} = 0
\]

\[
\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_2}\right) - \frac{\partial L}{\partial q_2} = u
\]

where \(u\) is the torque applied to the AMCES axis, and \(t\) is the time. Thus, the equation of motion is derived.

The authors have already confirmed that the above modeling results are consistent with the modeling results based on the multibody dynamics method (Hara and Nakagami, 2019).

4. Control system design

As mentioned in the introduction, the control system of the previous study was obtained by trial-and-error, and its robustness cannot be guaranteed against parameter uncertainties (Tsuchiya, et al. 2018). For ensuring motorcycle safety, a systematized control system design method is required. This section proposes a two-degree-of-freedom (2-DOF) control system design, as shown in Fig. 4. Here, the nominal system is the motorcycle system with the designed mechanical parameters. The real system is the motorcycle system with the mechanical parameter variations, for example, the nominal system with additional mass. The 2-DOF design enables unified control for standing up autonomously from the parked mode, and ensuring stability. We define the state variable vector consisting of the angle and angular velocity of each pendulum thus: \(x = (q_1\ \dot{q}_1\ q_2\ \dot{q}_2)^T\). Here, the state variable vector \(x\) is exactly equal to the measurement vector \(y\).

4.1 Feedforward control design (references and feedforward control input)

For standing up from the parked mode, this study designs a control system that consists of two phases. In Phase 1, Q1 leans on the kickstand; it moves away from the stand in Phase 2. Q2 is controlled to swing up in Phase 1. As a result, the center of the gravity of the entire system is designed to propel the whole system away from the stand. The \(q_2\) value is the trigger for the transition to Phase 2. Here, the angular velocity of \(\dot{q}_2\) is regulated within a certain value.

In Phase 2, gain scheduling is performed. The characteristics of the double pendulum are taken into consideration in this phase. The center dashed line in Fig. 3 is the vertical line from the grounding point of MOTOROiD. If the center of gravity of the whole system is maintained on the line, the whole system achieves a stable status even if \(q_1 \neq 0\). This fact proves the existence of the equilibrium point and the linear approximation model corresponding to each value of \(q_1\). The proposed control system uses the time-varying equilibrium point at 3° closer to the origin point from \(q_1\) at each time step. The linear approximation is applied around that point to perform LQR design (Green and Limebeer, 1995). At each step, we set the equilibrium point anew, and obtain the LQR gains. Subsequently, the optimal control at each step is performed consistently.

The reference input and trajectories can be obtained by applying the above control system to the nominal system.

4.2 Feedback control design (feedback control input of the error system)

There are some risks arising from constituting the control system entirely of the feedforward control input. The required value of \(q_2\) to achieve Phase 2 in the real system may differ from that in the nominal system. Therefore, the feedback controller adjusts the reference control input to achieve the transition to Phase 2. In this case, the controller extends the time of the Phase 1 control profile by continuing the last input until transition to Phase 2 is achieved. As a
result, the Phase 2 system transition can be achieved even if the required value of $q_2$ is larger than that in the nominal system.

In Phase 2, the feedback control is performed using the error system. Let $t$ be the time since the transition to Phase 2. The error vector $e(t)$ of the state variables between the nominal system and the real system is represented thus:

$$e(t) = x_{\text{ref}}(t) - x(t).$$  \hspace{1cm} (17)

If the real system and the nominal system are completely similar, $e(t) \equiv 0$. However, errors occur in the state variables of the real system and the corresponding reference trajectories due to parameter fluctuation and modeling error. Here, the error vector $e(t)$ is suppressed by the proposed feedback control method. The feedback control system can be designed as a feature of 2-DOF. This study applies the LQR similar to the reference trajectories design to achieve feedback control. It takes uncertainties into account. Other controller designers may use another feedback controller, such as the sliding mode controller, taking the actual condition of the controlled object into account. The feedback gains are obtained by varying the weighing matrix $Q$ to follow the reference trajectories in high accuracies.

5. Simulation examples

This section performs numerical simulations to verify the performance of the established control system. Here, we demonstrate case study scenarios with several conditions (Fig. 5) to prove the robustness of the proposed control system.

5.1 Step 1: Reference generation with the nominal system for standing up from the parking mode

Because the inclination of a typical parking motorcycle is $12^\circ$, we set the state variables in the parking mode as follows:

$$x = (q_1, \dot{q}_1, q_2, \dot{q}_2)^T = (12^\circ, 0, 0, 0)^T.$$  \hspace{1cm} (18)

The system constraints of the actual MOTOROiD are also introduced in the simulation condition. It is necessary that the $\dot{q}_2$ value does not become too large when transitioning to Phase 2. Therefore, we define the reference input in Phase 1 as follows:

$$u_{\text{ref}} = \begin{cases} 250 \text{ Nm} & (q_2 \leq 10^\circ) \\ 150 \text{ Nm} & (q_2 > 10^\circ) \end{cases}.$$  \hspace{1cm} (19)

We set the weighing matrices $Q$ and $R$ in the LQR design in Phase 2 as follows:

$$Q = 1.0 \times 10^4 \times \text{diag}[1 \hspace{0.5cm} 0.01 \hspace{0.5cm} 0.5 \hspace{0.5cm} 0.01]$$

$$R = 1$$  \hspace{1cm} (20)

The values of $Q$ and $R$ were determined by trial-and-error weighing of the angles.
The nominal system parameters are summarized in Table 1. These parameters are defined based on the actual MOTOROiD system. In addition, some actuation constraints are also defined based on the actual system, as described in Eq. (19). We assume that each component of MOTOROiD is rigid. The details are summarized in Fig. 6 (a). The upper figures show the state variables. The lower figure shows the time series control input histories. The time series inputs are stored as the reference input of each control time step. Here, the entire stabilizing control scenario achieves the required status within 5 s, and the authors generate the reference trajectories for 6 s.

5.2 Step 2: Verifying system robustness against uncertain parameters variations

| Parameter         | Symbol | Value | Unit |
|-------------------|--------|-------|------|
| Body length       | $l_1$  | 0.946 | m    |
|                   | $l_2$  | 0.604 |      |
|                   | $l_3$  | 0.821 |      |
|                   | $l_4$  | 0.250 |      |
| Axis angle        | $a_2$  | 40    | deg  |
| Inertia tensor    | $I_{1xx}$ | 7.20 | kg m$^2$ |
|                   | $I_{1yy}$ | 18.0 |
|                   | $I_{1zz}$ | 13.9 |
|                   | $I_{1xy}$ | 0.00 |
|                   | $I_{1xz}$ | 3.08 |
|                   | $I_{1yz}$ | 0.00 |
|                   | $I_{2xx}$ | 4.38 |
|                   | $I_{2yy}$ | 19.0 |
|                   | $I_{2zz}$ | 15.4 |
|                   | $I_{2xy}$ | 0.00 |
|                   | $I_{2xz}$ | -2.00|
|                   | $I_{2yz}$ | 0.00 |
| Body mass         | $m_1$  | 89.2  | kg   |
|                   | $m_2$  | 124   |      |

Then, we perform numerical simulations to verify the robustness of the designed 2-DOF. Here, three simulations cases are set to verify whether this control system enables MOTOROiD achieve autonomous standing up under various conditions. These cases are generally possible situations that take motorcycle parking conditions or the characteristics of MOTOROiD into consideration. The system’s robustness against weight variation has already been confirmed (Hara, et al., 2019). Therefore, the following three conditions are selected to complete the verification of the robustness of the control system against major parameter fluctuations.

The first case considers the parking mode variation. Here, MOTOROiD is parked with the front wheel on the upper side of a slope. Because motorcycle parking lots are not always flat, the system is required to be able to stand autonomously in spite of the slopes. We set a slope angle of 10$^\circ$.

The second case also considers parking mode variations. Here, we consider the Q1 variation in the parking mode. In the nominal mode, the angle at parking is set to 12$^\circ$; however, it is set to 10$^\circ$ in this simulation. It emulates the unevenness of the ground or the failure of the kickstand. This simulation verifies whether MOTOROiD can stand up without losing balance even under conditions varying from the initial conditions.

The third case considers the effect of the Coulomb friction torque on the AMCES axis. This situation is caused by friction between the rear wheel and the ground. This verification confirms how the friction of the ground affects MOTOROiD. In the simulation, we set the Coulomb friction torque $\tau$ as follows;
\[
\tau = \begin{cases} 
5 \text{ Nm; } \dot{q}_2 < -5.73 \text{ deg/s or } |\dot{q}_2| \leq 5.73 \text{ deg/s, } u < -5 \text{ Nm} \\
-u; |\dot{q}_2| \leq 5.73 \text{ deg/s, } |u| \leq 5 \text{ Nm} \\
-5 \text{ Nm; } \dot{q}_2 > 5.73 \text{ deg/s or } |\dot{q}_2| \leq 5.73 \text{ deg/s, } u > 5 \text{ Nm}
\end{cases}
\]

where \( u \) is the input torque.

These simulation conditions and their schemes are summarized in Table 2 and Fig. 5.

| No. | Condition |
|-----|-----------|
| 1   | Parking mode condition variation 1: The front wheel is on the upper side on a slope of 10° |
| 2   | Parking mode condition variation 2: \( Q_1 \) angle is 10°, different from 12° |
| 3   | Friction torque: 5 Nm Coulomb friction on the AMCES axis |

Fig. 5  Schemes of the simulation conditions
(b) Comparison results between the nominal system and Case 1

(c) Comparison results between the nominal system and Case 2
Comparison results between the nominal system and Case 3

Fig. 6   Simulation results

Fig. 7   Simulation result of Case 2 with the maximum input constraints

We set the weighing matrices $Q$ and $R$ in the LQR design used for the feedback controller according to the previous research (Hara, et al., 2019) as follows:

$$Q = 1.0 \times 10^5 \times \text{diag}[1, 0.01, 0.5, 0.01],$$
$$R = 1$$

(22)

The results are summarized in Fig. 6 (b)–(d). Here, all the system responses align with the reference trajectories. The simulation result of Case 1 reveals overshoots at each angle. However, these overshoots converge immediately, and the convergence times are almost the same as the nominal system. Although the overshoots of the angles in Case 2 are similar to that of Case 1, the control input immediately following the phase transition is excessive, compared to the
nominal system. Therefore, we repeat the simulation, taking the input saturation of the AMCES axis into consideration. The results are shown in Fig. 7. Here, it is confirmed that MOTOROiD can stand up even when there are maximum input constraints on the AMCES axis. In Case 3, both the trajectories and the input align with the nominal system. However, it is confirmed that, unlike in the nominal system, the vibration does not converge because of the Coulomb friction torque near the convergence state where it is necessary to add a small input.

These numerical simulation results demonstrated that the robustness of the proposed control system against variations in the initial parking conditions or error variations in the control inputs can be achieved by designing the control system based on the mathematical model.

### 7. Conclusion

This study explored a systematic control system design method for a prototypical self-standable motorcycle, MOTOROiD with AMCES. The mathematical model was derived from Lagrange’s equation of motion. A unified control method for autonomously standing up from the parking mode and ensuring stability was introduced by using the 2-DOF control system structure. The effectiveness of the modeling and control system design was verified through several numerical simulations taking variations of the initial condition and Coulomb friction into consideration. The numerical simulation showed that the proposed control system was effective in realistic situations. Based on these results, we plan to conduct further experimental verification using a real MOTOROiD in future.

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