Steady locomotion in torso-actuated rimless wheel robots

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ABSTRACT

Rimless wheel robots are ground robots whose wheels have no rims or tires but only spokes. This paper considers torso-actuated wheel robots. Each robot considered in this paper is composed of a single wheel and a single torso connected to the wheel centre by an actuated revolute joint. The locomotion properties of the torso-actuated rimmed and the rimless wheel robots are unknown. This paper first investigates steady locomotion of a torso-actuated rimmed wheel robot theoretically. Then, steady locomotion of a torso-actuated rimless wheel robot is evaluated for various parameters by numerical simulations. Finally, similarities and differences between the rimmed and the rimless wheel robots are discussed. In particular, it is shown that the speed-maximizing posture is substantially shared among the rimmed and the rimless wheel robots. On the other hand, some other properties are not shared among them. The most significant difference is the relationship between the maximum steady speed and the wheel radius. It is concave in some parameter space for the rimless wheel robot, but is linear in the whole parameter space for the rimmed wheel robot.

1. Introduction

Rimless wheel robots are ground robots whose wheels have no rims or tires but only spokes. Spokes are in contact with the ground instead of tires. Rimless wheels have two distinct roles in robotics. One is to provide a simplified model of walking. The model is useful for analysis of human walking and controller design of legged robots [1–4]. The other is to change the mobility of wheeled robots. It has been demonstrated that rimless wheel robots have high mobility on a variety of terrains both indoors [5–9] and outdoors [10–12].

This paper considers torso-actuated wheel robots. Each robot considered in this paper is composed of a single wheel and a single torso connected to the wheel centre by an actuated revolute joint. The torso-actuated wheel robots are suitable for comparison between rimmed wheels and rimless wheels, since they have the simplest structure among others.

There have been proposed several controllers for torso-actuated rimless wheel robots [13–16]; however, their locomotion properties are poorly understood. For example, it remains to be seen what posture maximizes the steady speed. In addition, similarities and differences between the rimmed and the rimless wheel robots are unknown. They are discussed in this paper.

This paper first considers a torso-actuated rimmed wheel robot. Its steady locomotion is determined theoretically. This reveals several locomotion properties of the rimmed wheel robot. Then, a torso-actuated rimless wheel robot is considered. Its steady locomotion is evaluated for various parameters via numerical simulations. Finally, similarities and differences between the rimmed and the rimless wheel robots are investigated.

In particular, this paper discusses what posture maximizes the steady speed. It is demonstrated that the speed-maximizing posture is substantially shared among the rimmed and the rimless wheel robots. On the other hand, some other properties are not shared among them. The most significant difference is the relationship between the maximum steady speed and the wheel radius. It is concave in some parameter space for the rimless wheel robot, but is linear in the whole parameter space for the rimmed wheel robot.

2. Robot systems

This paper discusses steady locomotion of a rimless wheel with a torso illustrated in the left of Figure 1, and a rimmed wheel with a torso shown in the right of Figure 1. The main focus lies on the former, and the latter is used for comparison. Each robot considered in this paper is composed of a single wheel and a single torso connected to the wheel centre by an actuated revolute joint. It is assumed that the ground is flat and horizontal, because this paper investigates...
fundamental properties. It is also assumed that no slip occurs between the wheel and the ground, and that all the bodies and the ground are rigid.

Notations used in this paper are listed in Table 1. No notational distinction is made between the rimmed and the rimless wheel robots. The symbols in Table 1 are used for the rimmed wheel robot in Section 2.1, and after that they are used for the rimless wheel robot.

2.1. Rimmed wheel with a torso

The dynamics of the rimmed wheel robot can be described by Euler–Lagrange equations. They are given by

\[
M_c(\theta) \ddot{\theta} + h_c(\theta, \dot{\theta}) + g_c(\theta) = \begin{bmatrix} -1 \\ 1 \end{bmatrix} u, \tag{1}
\]

where

\[
M_c(\theta) = \begin{bmatrix} f_w + (m_t + m_w)\ell_w^2 & -m_t\ell_w \cos \theta_t \\ -m_t\ell_w \cos \theta_t & f_t + m_t\ell_t^2 \end{bmatrix}, \tag{2}
\]

\[
h_c(\theta, \dot{\theta}) = \begin{bmatrix} \dot{\theta}^2 m_t\ell_t \ell_w \sin \theta_t + c \dot{\theta} \\ 0 \end{bmatrix}, \tag{3}
\]

\[
g_c(\theta) = \begin{bmatrix} 0 \\ m_t \ell_t \sin \theta_t \end{bmatrix}. \tag{4}
\]

Note that \(h_c\) includes a frictional damping term.

Steady locomotion in the rimmed wheel robot is explored theoretically below. It is assumed that

\[
\dot{\theta}_w = 0, \quad \dot{\theta}_t = 0, \quad \text{and} \quad \dot{\theta}_1 = 0. \tag{5}
\]

The angles \(\theta_w\) and \(\theta_t\) are measured from the vertical axis, and the last equation of (5) implies no rotation of \(\theta_t\). Substituting (5) into (1) yields

\[
u = m_t \ell_t \ell_w \sin \theta_t, \tag{6}
\]

and

\[
\dot{\theta}_w = -\frac{m_t \ell_t \ell_w \sin \theta_t}{c}. \tag{7}
\]

The translational velocity of the wheel in the \(x\)-direction in steady locomotion, given by

\[
\dot{x}_w = \ell_w \dot{\theta}_w = -\frac{m_t \ell_t \ell_w \sin \theta_t}{c}, \tag{8}
\]

is simply called the steady speed. Consider two torso angles \(\theta_{t1}\) and \(\theta_{t2}\) that satisfy

\[
\sin \theta_{t1} = \sin \theta_{t2}, \quad \cos \theta_{t1} > 0, \quad \text{and} \quad \cos \theta_{t2} < 0. \tag{9}
\]

Then, the two angles produce an equal value of the steady speed. This implies that there exist two driving modes in steady locomotion with \(\cos \theta_t \neq 0\). The mode with \(\cos \theta_t < 0\) is called the upper mode, and the other is called the lower mode in this paper. Let efficiency be defined as the ratio of the movement distance to the total applied torque per rotation. The efficiency in steady locomotion is given by

\[
r_c = \frac{t_w \dot{x}_w}{t_w \ell_w} = \frac{\ell_w}{c}, \tag{10}
\]

where \(t_w\) stands for the rotation period of the wheel, and the second equality follows from (6) and (8).

Steady locomotion can be summarized as follows.

(a) The steady speed is maximized, when the torso is in the horizontal posture, or equivalently, when \(\cos \theta_t = 0\).

(b) There exist two driving modes in non-horizontal posture.

(c) The efficiency is invariant against \(\theta_t\).

(d) The steady speed is symmetrical with respect to the horizontal posture.

(e) The efficiency depends only on \(\ell_w\) and \(c\). It increases linearly with \(\ell_w\).

2.2. Rimless wheel with a torso

The rimless wheel robot moves along with collisions of spokes with the ground, while there is no collision in the rimmed wheel robot. A spoke that is contact with the ground is called the stance spoke. The stance spoke is changed after collision in steady locomotion as depicted in Figure 1.

The rimless wheel robot is a hybrid dynamical system with continuous dynamics and discrete dynamics. The continuous dynamics are described by Euler–Lagrange equations, and the discrete dynamics are given by state-transition equations during collision and a condition for collision occurrence. The state variables are reset in accordance with the state-transition equations, when a spoke collides with the ground. Otherwise, the motion is governed by Euler–Lagrange equations.
The continuous dynamics are represented as

$$M_r(\theta) \ddot{\theta} + h_r(\theta, \dot{\theta}) + g_r(\theta) = \begin{bmatrix} -1 \\ 1 \end{bmatrix} u,$$  

(11)

where

$$M_r(\theta) = \begin{bmatrix} J_w + (m_t + m_w) \ell_w^2 \\ -m_t \ell_w \cos(\theta_t - \theta_w) \\ -m_t \ell_w \cos(\theta_t - \theta_w) \end{bmatrix},$$  

(12)

$$h_r(\theta, \dot{\theta}) = \begin{bmatrix} m_t \ell_w \sin(\theta_t - \theta_w) \dot{\theta}_w^2 + c \dot{\theta}_w \\ -m_t \ell_w \sin(\theta_t - \theta_w) \dot{\theta}_w^2 \\ \end{bmatrix},$$  

(13)

$$g_r(\theta) = \begin{bmatrix} -(m_t + m_w) \ell_w g \sin \theta_t \\ m_t \ell_w g \sin \theta_t \end{bmatrix}.$$  

(14)

It is assumed that the joint is backdrivable and that collisions are perfectly inelastic. Then, the discrete dynamics [17] are written as

$$Q_p \dot{\theta}_{+} = Q_m \dot{\theta}_{-},$$  

(15)

$$\theta_{w+} = \mp \frac{\pi}{n},$$  

(16)

where

$$\theta_{w-} = \frac{\pi}{n}, \quad \dot{\theta}_{w-} > 0, \quad \text{and} \quad \alpha(\theta_t) \geq 0,$$  

(17)

or when

$$\theta_{w-} = -\frac{\pi}{n}, \quad \dot{\theta}_{w-} < 0, \quad \text{and} \quad \alpha(\theta_t) \geq 0,$$  

(18)

with

$$Q_p = \begin{bmatrix} J_w + (m_t + m_w) \ell_w^2 \cos \left( \theta_t \pm \frac{\pi}{n} \right) \\ -m_t \ell_w \cos(\theta_t \mp \frac{\pi}{n}) \\ -m_t \ell_w \cos(\theta_t \mp \frac{\pi}{n}) \end{bmatrix},$$  

(19)

$$Q_m = \begin{bmatrix} J_w + (m_t + m_w) \ell_w^2 \cos \left( \frac{2\pi}{n} \right) \\ -m_t \ell_w \cos \left( \theta_t \pm \frac{\pi}{n} \right) \\ -m_t \ell_w \cos \left( \theta_t \mp \frac{\pi}{n} \right) \end{bmatrix},$$  

(20)

$$\alpha(\theta_t) = J_w(\ell_t + m_t \ell_t^2) + m_t \ell_t^2 \ell_w^2 \cos^2 \frac{\pi}{n} - \cos^2 \theta_t$$  

$$+ \left\{ (m_w + m_t) \ell_t + m_t m_w \ell_t^2 \right\} \ell_w^2 \cos \frac{2\pi}{n},$$  

(21)

where the upper signs of ± and ± are used for $\dot{\theta}_{w-} > 0$, and the lower ones for $\dot{\theta}_{w-} < 0$. Equation (15) is equivalent to conservation of angular momentum during collision [17]. Due to (16), the wheel angle $\theta_w$ is always defined between the stance spoke and the vertical axis. Equation (16) is not necessarily required for representing the discrete dynamics. It simplifies the mathematical description above and improves the graphical representation of steady locomotion in the next section. In each of (17) and (18), the first and second equations give a condition for collision occurrence. The third equation is a necessary and sufficient condition that (15) holds. It also guarantees that $\text{sgn} \dot{\theta}_{w-} = \text{sgn} \dot{\theta}_{w+}$. Conversely, if $\alpha < 0$, then $\dot{\theta}_{w+}$ is reset to zero, which is undesirable for steady locomotion. The case of $\alpha < 0$ did not appear in numerical simulations given in the next section, and the dynamics for $\alpha < 0$ are not described in this paper. See [17] for details of the discrete dynamics.

Steady locomotion can be achieved by a PID controller represented by

$$u = K_p(\theta_t - \theta_{t_i}) + K_d \dot{\theta}_t + K_i \int_{t=0}^{t} (\theta_t - \theta_{t_i}) \, dt,$$  

(22)

where $\theta_{t_i}$ is a desired torso angle, and $K_p$, $K_d$, and $K_i$ are control gains [13,16]. The PID controller is adopted in this paper for the following three reasons:

![Figure 1](image_url)

Figure 1. Left: rimless wheel robot in steady locomotion. Right: rimmed wheel robot. Each robot is composed of a wheel and a torso. The angles $\theta_w$ and $\theta_t$ are measured from the vertical axis, and defined positive in the clockwise direction. The ground is assumed to be flat and horizontal.
Table 2. Parameters in numerical simulations.

| $\theta_s$ | $m_l$ | $\ell_l$ | $m_w$ | $\ell_w$ | $n$ | $\ell_m$ | $j_1$ | $j_2$ | $\ell_c$ |
|-----------|-------|---------|-------|---------|-----|---------|------|------|-------|
| Defaults  | $-\pi/2$ | 1.0     | 0.4   | 1.0     | 1.0 | 1.0     | 1.0  | 1.0  | 1.0   |
| Increments| $\pi/180$ | 0.1     | 0.1   | 0.1     | 0.1 | 1       |      |      |       |

- It is primitive.
- It provides steady locomotion at convergence, if parameters and initial state variables are appropriately tuned.
- Steady locomotion is also achieved by the PID controller at convergence for the rimmed wheel robot given in Section 2.1.

The second property will be exploited to obtain steady locomotion for various values of parameters in numerical simulations demonstrated in the next section.

3. Steady locomotion of the rimless wheel robot

3.1. Examples of steady locomotion

Three examples of steady locomotion of the rimless wheel robot can be seen in Figure 2, where the PID controller (22) was applied. The control gains were set to high gains of

$$K_p = 100, \quad K_d = 100, \quad \text{and} \quad K_i = 100, \quad (23)$$

or low gains of

$$K_p = 2, \quad K_d = 2, \quad \text{and} \quad K_i = 2. \quad (24)$$

The length $\ell_l$ was set to 0.4 in the left and the middle of Figure 2, and to 1.0 in the right. The other parameters were set to the default values given in Table 2. The three examples were obtained at convergence from appropriate initial state variables in numerical simulations. Initial state variables were tuned by trial and error. This was achieved with a little effort, when the initial value of $\theta_w$ was set to a large value.

If the state variables follow the same pattern every $p$ collisions, then it is said that steady locomotion has period-$p$. The wheel angle $\theta_w$ is reset after each collision according to (16). Therefore, peaks of $\theta_w$ in Figure 2 represent collision occurrence. In the left or the middle of Figure 2, the state variables follow the same pattern every collision, and their locomotion has period-1. In the right of Figure 2, the state variables follow the same pattern every 16 collisions, and its locomotion has period-16. This implies that the number of collisions per pattern is neither a multiple nor a divisor of the number of the spokes in general.

The authors suppose that the low gains of (24) are near the lower end for steady locomotion with the default values of the parameters. If the control gains are smaller, then steady locomotion is not achieved or it takes a very long time for convergence. Examples of convergence times are listed in Table 3, where $\theta_w$ was initialized to a value in steady locomotion plus 0.1 and the other state variables were to values in steady locomotion. When the PID gains were larger than or equal to 1.3, steady locomotion with period-1 was achieved at convergence. When the gains were set to 1.2, the behaviour appeared to converge to one in steady locomotion with period-7, but it did not fully converge until the time $t$ exceeded 1000 seconds, where the state variables were initialized to values in steady locomotion with $K_p = K_d = K_i = 1.3$. In Table 3, steady locomotion with period-1 was determined, if a collision index $k$ satisfied all of

$$e(\theta_1, k) < 10^{-3}, \quad e(\theta_w, k) < 10^{-3}, \quad e(\theta_2, k) < 10^{-3},$$

$$e \left( \int_{t=0}^{t} (\theta_t - \theta_0) \, dt, k \right) < 5.0 \times 10^{-2}, \quad (25)$$

where

$$e(x, k) = \frac{\max_{x \in I_k} |x(t_k)_{+} - x(t_{k-1})_{+}|}{\max_{x \in I_k} x(t_{k}) - \min_{x \in I_k} x(t_{k})}, \quad (26)$$

$$I_k = \{ k - 10, k - 9, \ldots, k - 1 \}, \quad (27)$$

$$T_k = [ t_{k-1_{++}}, t_{k_{++}} ]. \quad (28)$$

The error defined in (27) denotes the amount of change in 10 values after collision. It is normalized by the amount of change between the last two collisions. The tolerance in (26) is larger than the others, since the integral of $\theta_t - \theta_0$ varies very little. The small variations can be confirmed in the bottom left and the bottom middle of Figure 2.

3.2. Computation of steady speed and efficiency

The distance per one step is provided by

$$2 \ell_w \sin \frac{\pi}{n}. \quad (30)$$

The average of the steady speed and the efficiency in steady locomotion with period-$p$ are given by

$$\ddot{x}_{\text{wave}} = \frac{2 \ell_w p \sin \frac{\pi}{n}}{(t_{k+p} - t_k)}, \quad (31)$$

$$r_r = \frac{2 \ell_w p \sin \frac{\pi}{n}}{\int_{t=t_k}^{t=t_{k+p}} |\tau(t)| \, dt}. \quad (32)$$
Figure 2. Three examples of steady locomotion with the PID controller (22). The length $l_t$ was set to 0.4 in the left and the middle, and to 1.0 in the right. The other parameters were set to the default values given in Table 2. The high gains of (23) were applied in the left, and the low gains of (24) were applied in the middle and right. The middle gain case of (33) is omitted due to space reasons. The vertical dotted lines in the right are drawn every 16 collisions.

respectively. They are obtained for different values of parameters by numerical simulations as follows (see also Figure 3):

1. Set the control gains to (23), (24), or middle gains of

   \[ K_p = 10, \quad K_d = 10, \quad \text{and} \quad K_i = 10. \]  

2. Choose a parameter of interest from $m_t$, $l_t$, $m_w$, $l_w$, and $n$.

3. Set all the parameters to the default values in Table 2. Initialize the state variables to those in steady locomotion for the default values.

4. Calculate the state variables at each time from the model of (11)–(21), until one of the followings is satisfied.

   A) It does not hold that $\alpha \geq 0$ during collision, where $\alpha$ is defined in (21).

   B) The direction of the wheel rotation is reversed, and the hind spoke touches the ground.

   C) A collision index $k$ satisfies all of (25) and (26).

   D) The time $t$ exceeds 1000 seconds.

   If C or D is satisfied, then go to Step 5. Otherwise, go to Step 6.

5. Perform the following three steps:

   i) Increase or decrease the desired torso angle $\theta_{t_d}$ by $\pi/180$. 

   ii) Return to Step 2.

   iii) Goto Step 4.
(ii) Initializethe state variables to those at the end of Step 4.

(iii) Goto Step 4.

(6) If $\theta_{td}$ is $-\pi/2$, then go to Step 8. Otherwise, go to Step 7.

(7) Perform the following four steps:

(i) Set the desired torso angle $\theta_{td}$ to $-\pi/2$.

(ii) Increase or decrease the value of the parameter of interest by the incremental value in Table 2.

(iii) Initializethe state variables to those in steady locomotion for the previous values of the parameters with $\theta_{td} = -\pi/2$.

(iv) Go to Step 4.

(8) If all the parameters were evaluated, then go to Step 9. Otherwise, choose another parameter of interest, and go to Step 2.

(9) If the three sets of gains were evaluated, then terminate the numerical simulation. Otherwise, choose another set of gains, and go to Step 2.

This paper investigates the five design parameters seen in Step 2. They can be easily changed in practice and the others not. For example, the rolling friction coefficient $c$ depends on the ground situation. The moments of inertia of a body depends on many physical factors such as the shape, and it is changed by changing the mass or the length.

If the state variables are initialized close to those in steady locomotion, then steady locomotion is achieved at convergence in a short time. For two parameter sets that are close to each other, it is expected that their locomotion patterns are close to each other in many cases. Therefore, Steps 3, 5-(ii) and 7-(iii) are reasonable for initialization.

If C is true at Step 4, then steady locomotion with period-1 is found.

The program run on seven computers in parallel. Each computer had an Intel Core i7-9700 processor at 3.00 GHz with 16 GB RAM, and the operating system was Windows 10. It took six days to complete the process.

3.3. Results and discussions

Simulation results are summarized in Figures 4, 5 and 6. The conditional A at Step 4 was never true in the simulation results. The followings can be found from the figures.

(a’) In most settings, the steady speed is maximized when $\theta_{td}$ is nearly in the horizontal posture, as can be seen in Figures 4 and 5. In particular, the speed maximizing angles in steady locomotion with period-1 are within $\pm4\pi/180$ radians from the horizontal posture. They are very close to the horizontal posture, if the middle gains are applied.

(b’) There exist two driving modes, which can be confirmed in Figure 4.

(c’) Figure 4 shows that the steady speed is not symmetrical with respect to the horizontal posture. It is almost symmetric, when high gains are applied. Low gains keep the upper mode within a very limited range of the desired torso angle.

(d’) The maximum steady speed increases almost linearly with each of $m_t$ and $\ell_t$. It decreases almost linearly with $m_w$. It is concave with respect to $\ell_w$. They can be seen in the left of Figure 6.

(e’) The efficiency is not constant against $\theta_{td}$, but is almost constant around $\theta_{td} = -\pi/2$, as can be found in the right of Figure 4.

(f’) The efficiency depends on many parameters. In particular, it is concave with respect to $\ell_w$. They can be seen from the right of Figure 6.

(g’) Both the maximum steady speed and the efficiency monotonically increase with respect to $n$.

Similarities and differences between the rimmed and rimless wheel robots can be captured by comparing between (a)–(f) in Section 2.1 and (a’)–(f’). As an example of the similarities, steady speed is maximized in the horizontal posture for the rimmed wheel robot, and it is maximized around the same posture for the rimless wheel robot in steady locomotion with period-1.
The wheel radius is an important parameter for both the rimmed and the rimless wheel robots, but it plays different roles for different robots.

- For the rimmed wheel robot, the efficiency depends only on two parameters as described in (f). They are the wheel radius and the rolling friction coefficient. The rolling friction coefficient cannot be changed arbitrarily, since it is an environmental parameter that depends on the ground. Therefore, the wheel radius is the only useful parameter that improves the efficiency.

- For the rimless wheel robot, both the maximum steady speed and the efficiency are concave with respect to the wheel radius. There exists an optimal value of the wheel radius for each of the maximum steady speed and the efficiency. This is a unique characteristics found in this study, although the search space is limited in this study.

4. Concluding remarks

This paper investigated steady locomotion of torso-actuated wheel robots. The dynamics of the rimmed
Figure 6. Maximum steady speed and efficiency. For each plot, the parameter on the x-axis is a variable, the desired torso angle $\theta_{td}$ is set to the speed-maximizing posture, and the other parameters were set to the default values. This figure is plotted in the same manner as Figure 5.

and the rimless wheel robots were compared. Then, similarities and differences between them were discussed. In particular, it was demonstrated that steady speed is maximized in the horizontal posture for the rimmed wheel robot, and it is maximized around the same posture for the rimless wheel robot instead by locomotion with period-1. On the other hand, it was shown that the wheel radius plays different roles for different robots. For the rimless wheel robot, both the maximum steady speed and the efficiency are concave with respect to the wheel radius in some parameter space. Meanwhile, they are linear with respect to the wheel radius in the whole parameter space for the rimmed wheel robot.

The torso-actuated wheel robots have two driving modes: the upper mode and the lower mode. For the rimless wheel robot, the upper mode is more important than the lower mode. One of the main roles of the rimless wheel is to improve mobility on uneven terrains, as described in Section 1. The upper mode is suitable for, for example, stair-climbing and stepping over obstacles. For example, let it be supposed that the torso length is
longer than the wheel radius. Then, the torso may hit a stair in the lower mode, since the torso is positioned in front of the wheel centre in steady locomotion. It can be avoided in the upper mode. For another example, let it be supposed that the rimless wheel robot is realized in the three-dimensional space. The rotation planes of the wheel and the torso are parallel at a distance. In the lower mode, even if the wheel steps over an obstacle, the torso may hit the obstacle or another obstacle. It also can be avoided in the upper mode. On the other hand, it was shown in this paper that low control gains keep the upper mode within a very limited range of the desired torso angle. A powerful actuator is practically required for the rimless wheel robot.

In this paper, steady locomotion was investigated numerically for the rimless wheel robot, while it was done theoretically for the rimmed wheel robot. The properties on the rimless wheel robot shown in this paper were confirmed only in limited regions of one-dimensional parameter space. The present numerical approach requires a lot of computation time even in one-dimensional parameter space. It is not suitable for analysis in multi-dimensional parameter space, since the computation time increases exponentially with the number of dimensions, or equivalently, the number of parameters. An effective numerical approach or a theoretical approach should be developed, which is left as future work.

One of the main contributions of this paper is to reveal differences between the rimmed and the rimless wheels. When steady locomotion is explored in multi-dimensional parameter space, the same results as this paper are obtained in the same limited regions as this paper. This guarantees that exploration in multi-dimensional parameter space is worth to spend much effort.

For the rimmed wheel robot, the PID controller achieves transition from standstill to steady motion. On the other hand, it depends on physical parameters for the rimless wheel robot. Roughly speaking, the PID controller achieves such transition for the rimless wheel robot, only if the number of spokes is large. Note that rimless wheels with many spokes are useless on uneven terrain, since such wheels cannot climb steep stairs or step over large obstacles. Therefore, a new form of transient locomotion that is suitable even for a small number of spokes is required.

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Disclosure statement

The authors report there are no competing interests to declare.

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Notes on Contributors

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