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# Optimized non-reciprocating legged gait for an eccentric paddle mechanism

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## HIGHLIGHTS

- Optimal force condition can be achieved by keeping supporting paddle vertical.
- Increased vertical parameter can optimize the non-reciprocating legged gait.
- The performance can be improved by increasing locomotion velocity and period.
- Enlarging stride length can improve the locomotion performance of the mechanism.

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## ABSTRACT

To reduce the influence of gear backlash, a novel gait named non-reciprocating legged gait for the eccentric paddle (ePaddle) mechanism has been proposed in our previous study. In the gait, all the actuators rotated in one direction without the reciprocating. Based on force analysis of the supporting paddle, this work found that the locomotion performance of the mechanism can be further improved by keeping the supporting paddle vertical for a longer time of the supporting phase. Thus, vertical parameter which denotes the time rate of vertical state to supporting phase is proposed for gait planning. The experiments are performed to verify the validity of the proposed optimized non-reciprocating legged gait, and to identify the effects of the locomotion velocity, period, and vertical parameter on output torque and power of the mechanism. It can be found that comparing with the non-reciprocating legged gait, the locomotion performance of the mechanism is significantly improved by the optimized gait.

## 1. Introduction

In recent years, the amphibious robots with high environmentally adaptability have gained great potential to assist in accomplishing tasks in dangerous environments, such as disaster rescue, anti-terrorism riot, underwater ecological environment detection, terrain mapping, etc. Due to their superior mobility in both terrestrial and aquatic environments, the amphibious robots have drawn more and more attention from government agencies and research organizations.

The existing amphibious robots can be classified as biomimetic amphibious robots and hybrid-mechanism-based robots. The former are inspired from the morphological feature of natural creatures, such as snake-like robot [1], salamander-like robot Pleurobot [2], cockroach-like robot RHex [3], crab-like robot [4], turtle-like robot [5], etc. Amphibious robots based on hybrid mechanism achieve amphibious mobility by integrating several basic motion units into one locomotion mechanism, such as wheel–leg-integrated robot Seadog [6], leg–flipper-integrated robot MiniTurtle-I [7], leg–paddle-integrated robot AmphiHex-I [8] and Wheel–propeller–fin robot AmphiRobot-II [9]. The key factors limiting the application of the amphibious robots lie in their mobility, efficiency and load capability.

To enhance the mobility of the robot in complex amphibious environment, an innovative locomotion mechanism named ePaddle (eccentric paddle) mechanism has been proposed in our previous works [10]. It is able to perform several locomotion gaits with one mechanism in various environments. On terrestrial terrains, it can adopt legged crawling gait and legged race-walking gait [11,12]. In addition, the paddle can be penetrated into the soft soil to gain the additional drawbar pull and vertical force for accessing soft terrains [13]. Two kinds of aquatic paddling motions, rotational paddling mode and oscillating paddling mode, are suitable for swimming in aquatic environments [14,15].

Based on the terrestrial experiments, it has been found that the locomotion accuracy and efficiency of the legged gait are

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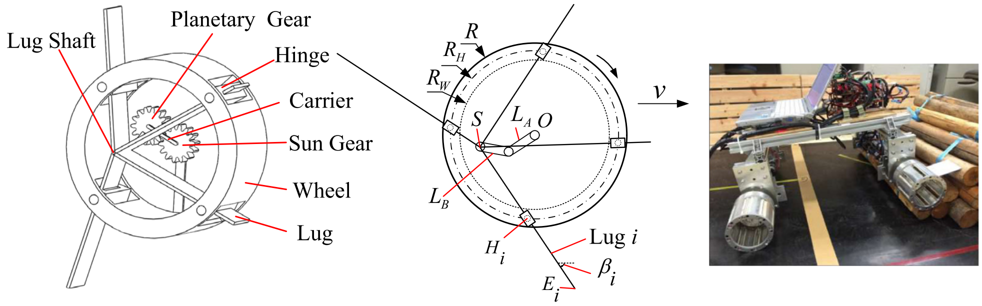

(a) (b) (c)

**Fig. 1.** Schematic of ePaddle: (a) mechanism, (b) kinematical diagram, (c) prototype.

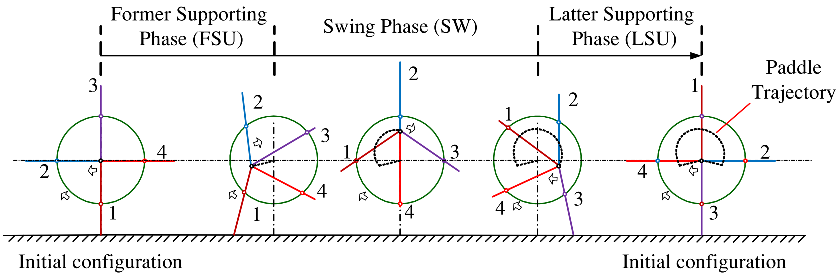

**Fig. 2.** Legged gait sequence.

significantly weakened due to the gear backlash of the ePaddle mechanism. Traditional anti-backlash methods, such as equipping the gear train with specially designed mechanical backlash-elimination devices and programmatic compensating backlash in motion planning algorithms, complicate the design, control and maintenance of the mechanism. In the previous study, a novel gait named non-reciprocating legged gait has been proposed [16]. In which, all the actuators rotated in one direction without reciprocating during the walking, and the performance improvements in locomotion accuracy and energetic efficiency have been verified by the experiments.

This study aims to optimize the proposed non-reciprocating legged gait for achieving better performance. The paper is organized as follows. Section 2 introduces the concept and non-reciprocating legged gait of the ePaddle mechanism. The optimized non-reciprocating legged gait is proposed in Section 3, and the validity is verified by the experiments in Section 4. Conclusions and plans for future studies are presented in Section 5.

## 2. Eccentric paddle (ePaddle) mechanism

### 2.1. Prototype mechanism

The ePaddle concept is first proposed in [10]. It comprises a wheeled shell and a set of lugs, and has three degrees of freedom as shown in Fig. 1(a). The main components are described below:

(1) A rotational joint driven by a motor for rotating the wheel shell. The hinges can passively rotate around the shaft affixed to the wheel rim, allowing retraction or protrusion of the lug through the hinge.

(2) A planetary gear mechanism with a sun gear and a carrier actuated by two motors. This mechanism moves the lug shaft that is fixed on a disk integrated with the planetary gear. The center distance $L_A$ between the two gears equals the center distance $L_B$ between the planetary gear and the lug shaft; thus, the lug shaft can arrive at any position within a circle of radius $R_W = L_A + L_B$ as shown in Fig. 1(b).

**Table 1**
Specifications of the ePaddle module whose kinematical diagram is shown in Fig. 1(b).

| Parameters | Unit | Value |
|---|---|---|
| Lug length $L$ | [mm] | 89 |
| Lug width $B$ | [mm] | 32 |
| Lug thickness | [mm] | 2 |
| Shell radius $R$ | [mm] | 52 |
| Shell width | [mm] | 113 |
| Lug hinges layout circle radius $R_H$ | [mm] | 50 |
| Center distance $L_A$ | [mm] | 20 |
| Lug shaft layout circle radius $L_B$ | [mm] | 20 |
| Workspace radius $R_W$ | [mm] | 40 |
| Mass of the ePaddle module | [kg] | 3.8 |

The wheel, carrier, and sun gear are separately driven by three DC brushed motors, each with its own transmission system. As the wheel rolls forward, the position of the lug shaft changes, and the lugs are actively protruded or retracted through the hinges. The fabricated ePaddle is equipped with a set of four lugs, and a four-modules-prototype is shown in Fig. 1(c). To enhance their durability, the mechanism components were constructed from aluminum or stainless steel. The ball bearings were double shield types to prevent contamination of the bearing raceways. The wool felt sheet was installed in two adjacent components, allowing relative movement between the components for dust sealing. The specifications of the ePaddle module are listed in Table 1.

### 2.2. Legged gait sequence

Because each ePaddle module has three degrees of freedom, it can control the tip planar position $E_i$ and inclination angle $\beta_i$ (Fig. 1(b)) of one paddle only, and the motions of the remaining lugs are determined accordingly. Thus, it is possible that the paddle can be protruded from the wheel shell and contacted to the ground to achieve a legged walking gait as shown in Fig. 2. Within a period, the ePaddle mechanism starts from and completes to initial configuration, through the former supporting phase (FSU), the swing