2P4-11

Deep Reinforcement Learning PID Controller for Ultrasonic Linear Motor with Quadruped Stator

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1. Introduction

Ultrasonic Linear Motors (USLM) exhibit many advantages, such as small size, lightweight, and no electromagnetic interference, which have attracted attention worldwide. In 2020, Tanoue proposed a quadruped stator-based USLM,[1)] mimicking the motion of an inchworm. However, prior studies[1,2)] primarily concentrated on voltage control, overlooking the influence of phase, which posed challenges in achieving accurate and sustainable operations. In this study, we refined the platform's performance by altering the rod material and employed the combination of DRL and PID algorithms for precise position control through phase manipulation.

2. USLM Structure and Driving Principle

2.1 Structure of USLM

The USLM with a quadruped stator[1)] is shown in **Fig. 1(a).** The stator dimension was 20x10x6.7 mm^3. The piezo part (the black plate in Fig. 1(a)) is a C-203 piezoelectric rectangle plate (Fuji Ceramic Co.) with divided three driving electrodes. Three driving voltages are expressed as follows.

$$V_{L1} = A \cdot \sin(2\pi f t + \phi) \quad (1)$$
$$V_{B1-2} = B \cdot \sin(2\pi f t) \quad (2)$$
$$V'_{B1-2} = B \cdot \sin(2\pi f t + \pi) \quad (3)$$

The quadruped stator part was made of an A2017 duralumin metal plate with four legs.

2.2 Driving principle

The quadruped stator emulates the inchworm's movement, utilizing two vibration modes. To synchronize these modes, they need to be driven at the same frequency. Adjusting the dimensions of the USLM is essential to bring the resonant frequencies of the two modes close, facilitating feeding and clamping motions. The first longitudinal mode (L1 mode) takes charge of feeding motion. The first-second bending mode (B1-2 mode) drives the clamping motion. The four feet are divided into two sections, griping and releasing the slider in turns. The two motions are shown in Fig. 1(b). By controlling the phase between the two modes, the USLM can achieve slider motion at varying speeds and directions.

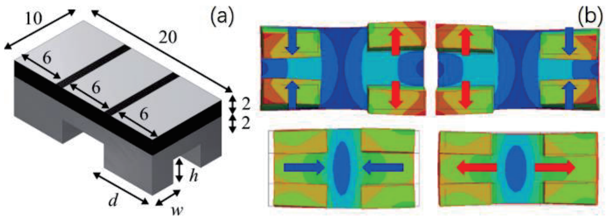

Fig. 1 (a) Schematic diagram of the USLM transducer. (b) The driving principle of the proposed USLM

3. Platform Construction and Modeling

3.1 Platform construction

The experimental platform is shown in **Fig. 2**. The PC communicates with the function generator to control its operations. It sends commands to generate and output the L1 and B1-2 driving signals, amplified by their respective amplifiers and transformer. These signals are then used for driving the stator transducer. At the same time, two current probes measure the induced currents of L1 and B1-2 to analyze their resonant conditions, while a laser displacement sensor measures the slider's position. The dSPACE transmits the data back to the PC.

3.2 Experiments with sliders with various materials

In an actual environment, the resonant states of the two modes can be influenced by multiple factors, including frequency, driving voltages, temperature, preload, wear status, and slider material. **Fig. 3** illustrates the impact of varying slider materials on the resonant frequencies of the two modes.

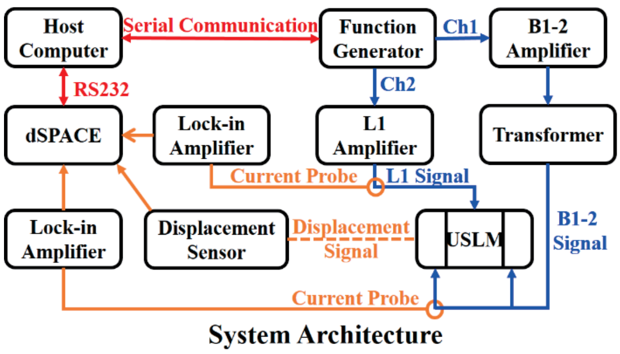

Fig. 2 System architecture of experimental platform

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In contrast to previous USLM research,[1,2] which predominantly employed metal rods as sliders, our innovative approach involves utilizing high-surface hardness engineering plastics such as PEEK as slider materials. This novel design reduces component wear, minimizes interference between modes, and significantly enhances the system's stability.

4. Deep Reinforcement Learning PID Controller

The PID (Proportional-Integral-Derivative) control has been widely used in diverse fields due to its impressive stability and effectiveness. However, the traditional PID control approach may need to be revised when dealing with real-time, dynamically changing nonlinear environments. This study introduces an innovative solution to address these challenges: a Deep Reinforcement Learning (DRL) [3] based PID controller (DRL-PID controller). Given DRL algorithms' decision-making speeds and complexities, we have developed and assessed an Advantage Actor-Critic (A2C) based PID controller in this research.

4.1 Training and Test in Simulation Environment

We proposed using PEEK as the rod material to reduce mutual interference. **Fig. 4(a)** shows the speeds at different phases when using the PEEK rod. We established a simulation environment grounded on the speed-phase relationship and integrated a DRL-PID controller that dynamically adapts PID's internal parameters in real-time, employing the A2C algorithm. Our comparison encompassed the performance of conventional PID, DRL-PID under training, and fully-trained DRL-PID, revealing DRL-PID enhanced precision in control (Fig. 4(b)).

4.2 Real-World Tests

In this section, we assessed controller performance on two distinct USLM motors (Motor-1 and Motor-2) in real-world (Fig. 4 (c)(d)). Due to the factors like errors, time delays, and inertia inherent to real-world environments, control outcomes were less favorable compared to simulations. Nevertheless, results revealed that the DRL-PID exhibited better robustness and steady-state response than the conventional PID. Notably, unlike the conventional PID, which diverged in Motor-2, the demonstrated DRL-PID showcased enhanced adaptability without needing per-environment tuning, revealing its potential benefits. Furthermore, with training, the performance of DRL-PID improved in both motors, confirming the positive impact of training in a simulation environment on control in real-world settings.

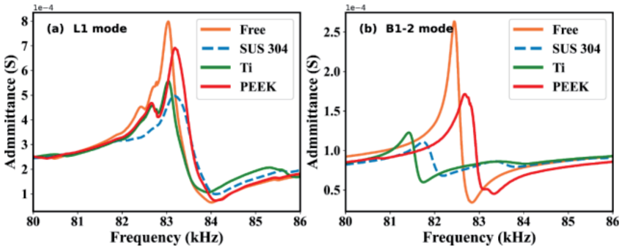

Fig. 3 (a)L1 mode status with varying material rods.
(b)B1-2 mode status with varying material rods.

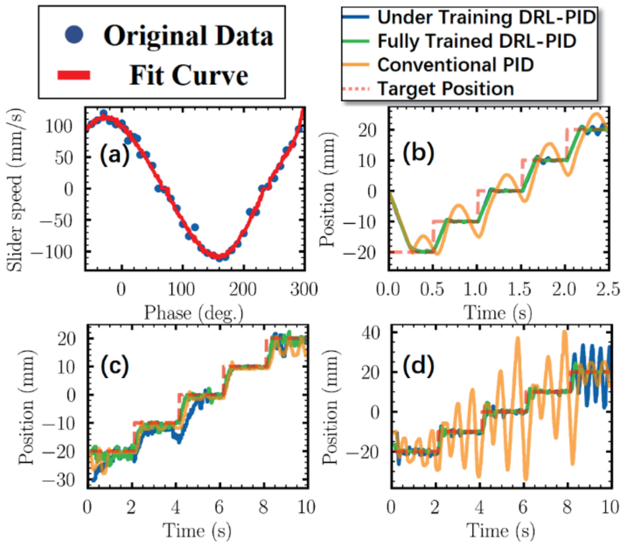

Fig. 4(a)The relationship of phase and slider speed
(b) DRL-PID controller in simulation.
(c) DRL-PID controller in USLM Motor-1
(d) DRL-PID controller in USLM Motor-2

5. Conclusion

In this study, we comprehensively understood the operational dynamics of the quadruped stator-equipped USLM. Subsequently, we designed a position control system utilizing a PEEK rod, specifically focusing on the DRL-PID controller customized for this configuration. To evaluate its effectiveness, we conducted comparative analyses involving the fully-trained, under-training DRL-PID controllers and the conventional PID controller under both simulated and real-world conditions. Our findings demonstrated that the DRL-PID controller exhibited superior performance, revealing enhanced capabilities after training.

Acknowledgment
This work was supported by SHINSEI Corporation and NACHI-FUJIKOSHI Corporation.

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