SCIENCE CHINA Information Sciences

Design and Attitude Control of a Novel Robotic Jellyfish Capable of 3D Motion

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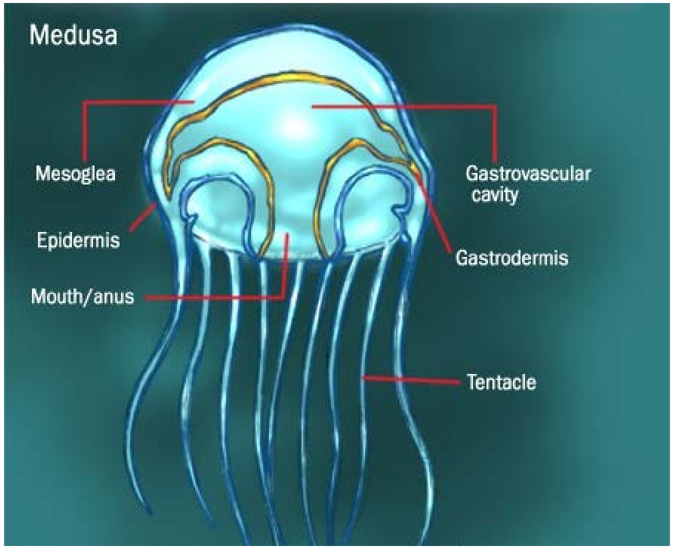
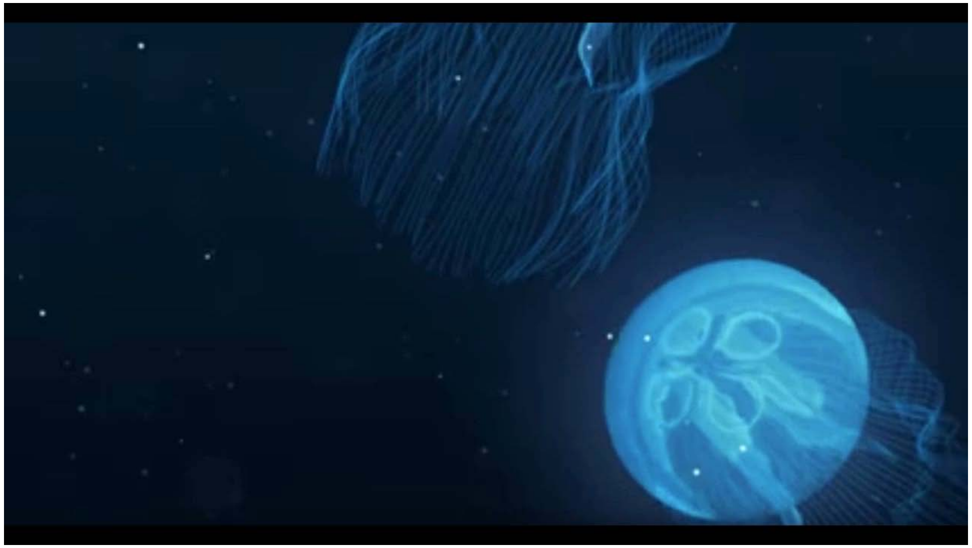
Outline

1. Introduction

A. Jet propulsion

- ☐ Jellyfishes propel themselves through their surroundings by radially expanding and contracting their bell-shaped bodies to push water behind them, which have been proven to be one of the most energetically efficient swimmers on the planet.
- ☐ Jellyfish-like swimming will have a remarkable propulsive advantage if low-energy propulsion is demanded.





1. Introduction

B. Robotic jellyfish

- Various robotic jellyfishes have been developed benefiting from the latest advancements in mechatronic design, materials, electronics, etc.

Most of existing robotic jellyfishes cannot freely adjust their three-axis attitude, which has an adverse effect on free-swimming propulsion and plausible applications.

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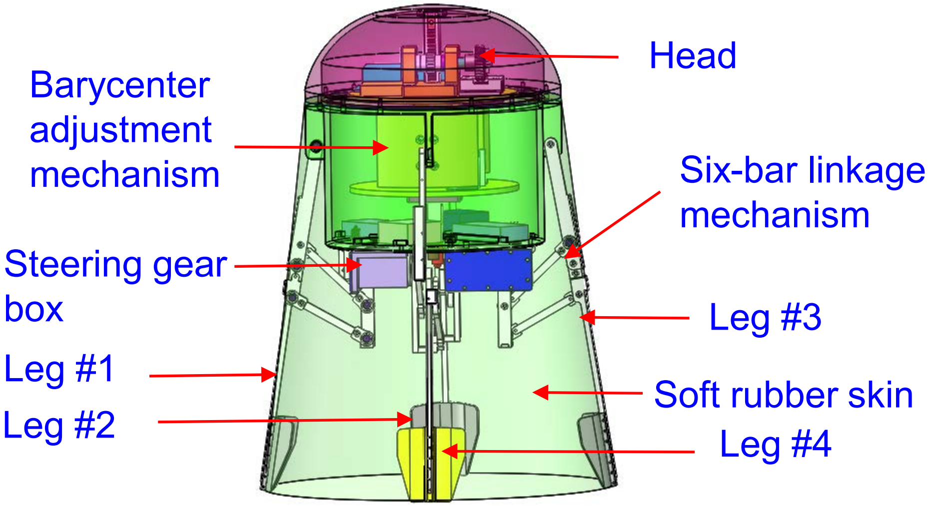
PART TWO

Development of the Robotic Prototype

2. Development of the Robotic Prototype

A. Robotic System Description

- The designed robotic jellyfish models after *Aurelia aurita* (moon jellyfish), which has relatively large displacement and is especially suited for use with large load capacity.



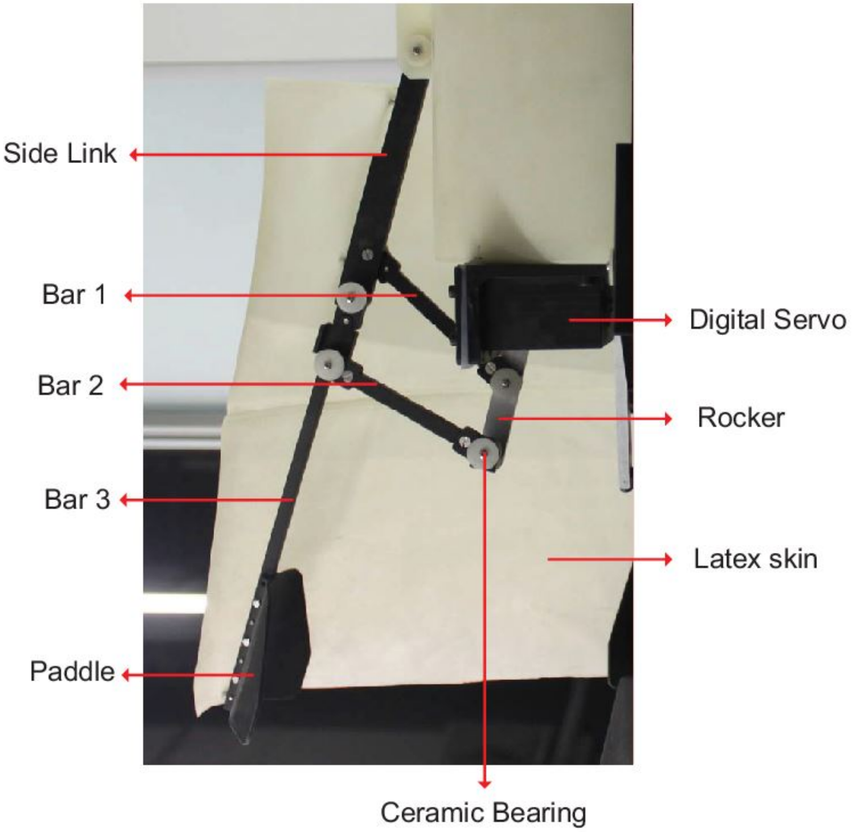
- Hemispherical in shape
- A bell-shaped rigid head
- A cylindroid main cavity
- Four separate six-bar linkage mechanisms
- A soft rubber skin

Items	Characteristics
Head	ϕ = 242 mm, h = 89 mm
Cavity	ϕ = 242 mm, h = 138 mm
Leg	331 mm (Length)
Mass	8.2 kg
Actuator	Four servos (HS-7980TH)
Sensors	IMU, Pressure
Controller	STM32F407

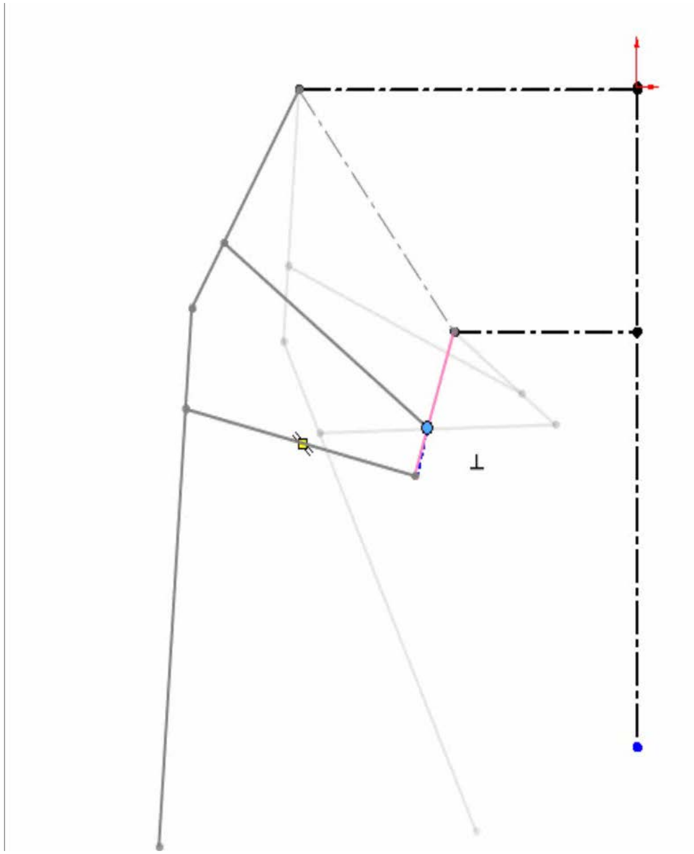
2. Development of the Robotic Prototype

B. Six-bar linkage mechanism

- The six-bar linkage structure is employed as main drive unit to convert the rotational motion of the servomotors to swing of the legs and generate propulsive thrust in water.



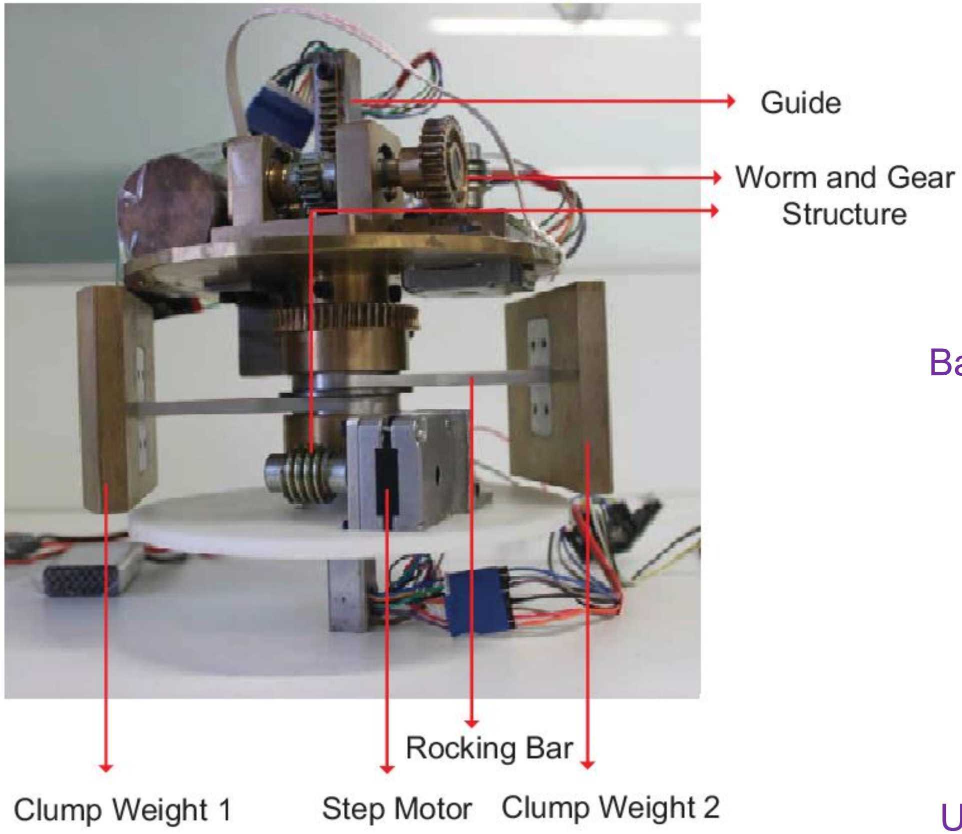
The six-bar linkage structure

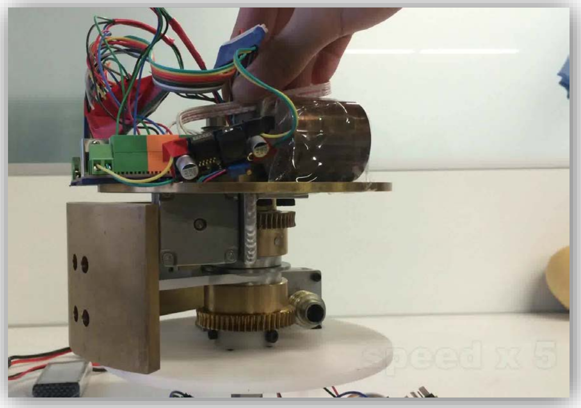


2. Development of the Robotic Prototype

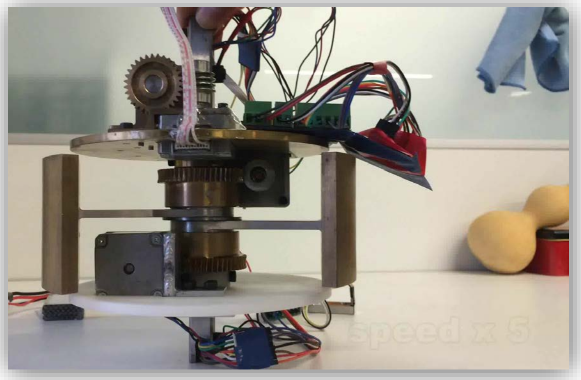
C. Barycenter adjustment mechanism

- A barycenter adjustment mechanism is particular introduced for flexible attitude control, which regulates the center of the gravity through both horizontally and vertically altering the relative position of two clump weights.





Balance movement in the horizontal direction

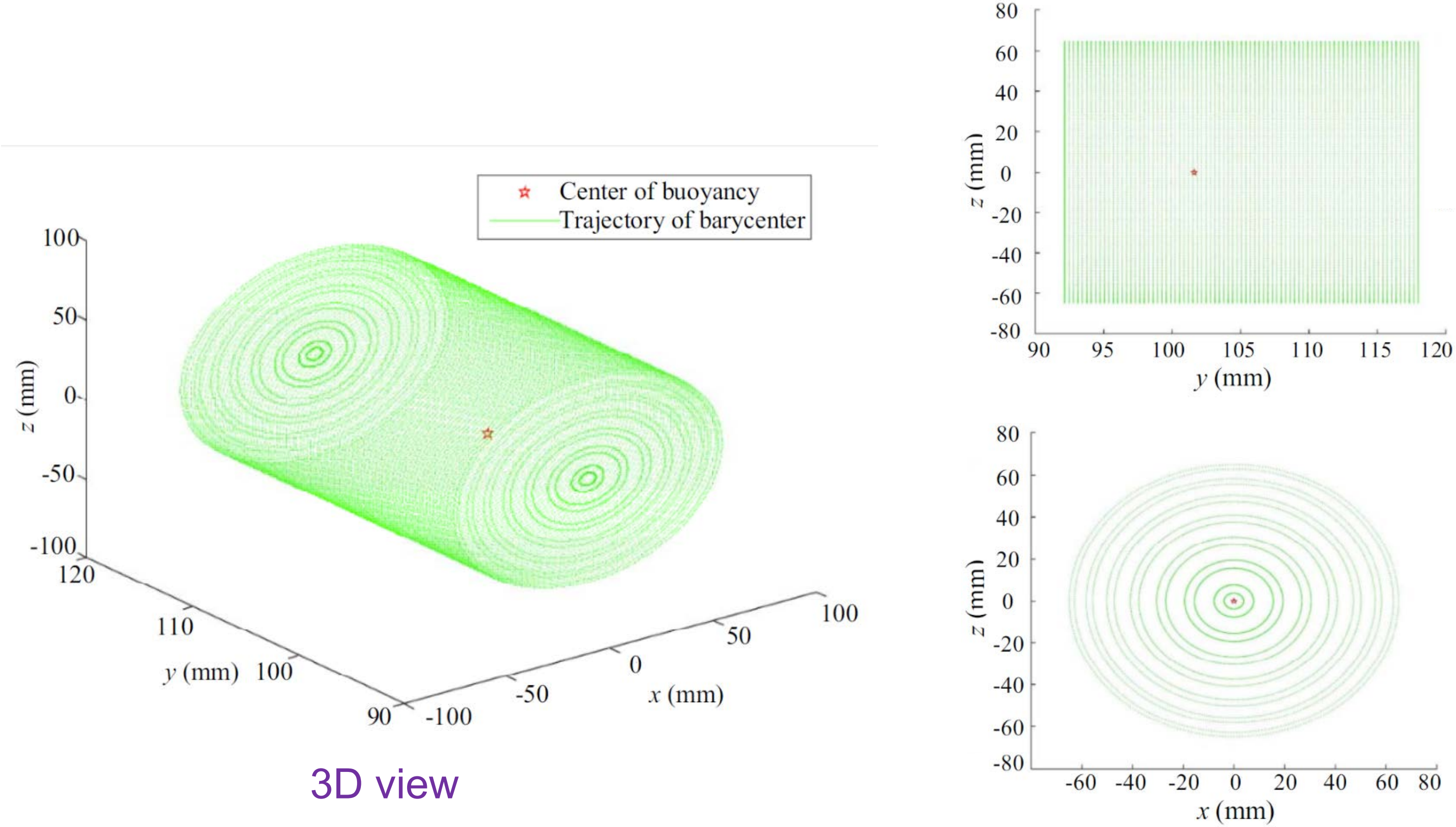


Up-down movement in the vertical direction

2. Development of the Robotic Prototype

C. Barycenter adjustment mechanism

- The locus of barycenter is able to enwrap the center of buoyancy.
  - 16 mm in the vertical plane (*y*-*z* plane)
  - 64 mm in the horizontal plane (*x*-*z* plane)



3D view

y-*z* plane

x-*z* plane

Relationship between the change of barycenter and the position of the buoyancy center from 3D view

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PART THREE

Reinforcement Learning Based Attitude Control

3. Reinforcement Learning Based Attitude Control

A. Q-learning

- A type of model-free reinforcement learning
- One of the most popular and powerful algorithms in real-world applications

The goal of Q-learning is to find a policy π^* that maximizes the reward received by the agent over time.

Q value (action-value)

$$Q^{\pi}(s_t, a_t) = \overbrace{r(s_t, a_t)}^{\text{Reward}} + \overbrace{\gamma \sum_{s_{t+1}} p_{s_t s_{t+1}} (\pi(s_t)) V^{\pi}(s_{t+1})}^{\text{Future discounted reward}}$$

Optimal policy

$$\pi^* = \arg\max_{a_t} Q(s_t, a_t)$$

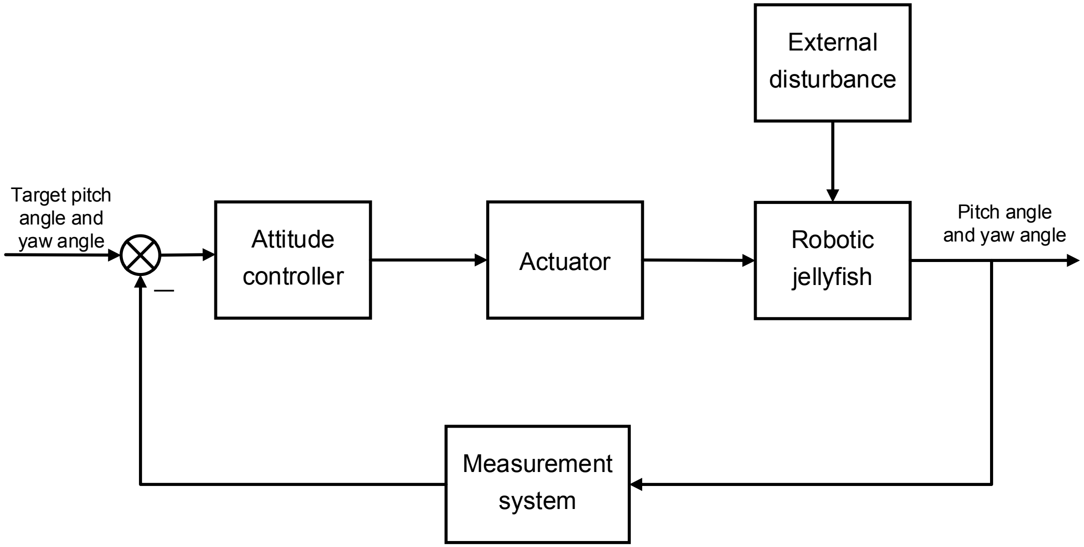
Updated value

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \overbrace{\alpha}^{\text{Learning rate}} \left[r(s_t, a_t) + \gamma \max_{a_{t+1}} Q(s_{t+1}, a_{t+1}) - Q(s_t, a_t) \right]$$

3. Reinforcement Learning Based Attitude Control

B. Attitude control

- Reinforcement learning has the ability to achieve adaptive controllers without access to accurate dynamical model, making it ideally suited for the flexible attitude control of the robotic jellyfish.
- Eliminate the burdensome process of tuning parameters and free the human resources and testing time to some extent.



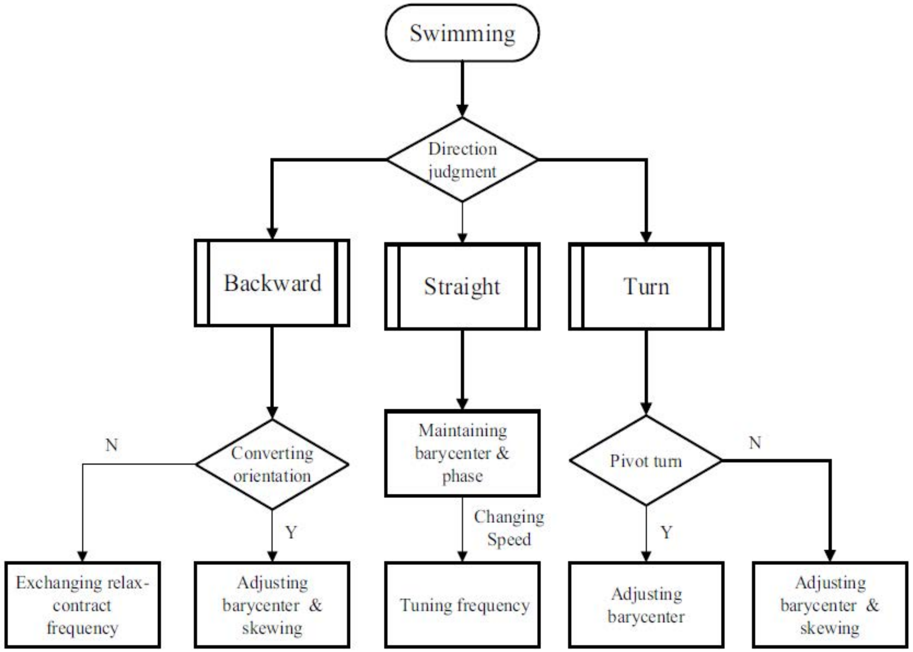
Block diagram of the proposed attitude control system of the robotic jellyfish

3. Reinforcement Learning Based Attitude Control

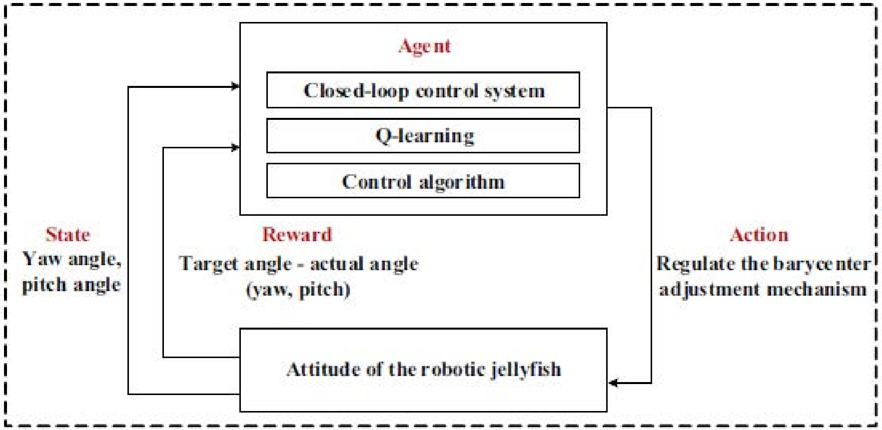
B. Attitude control

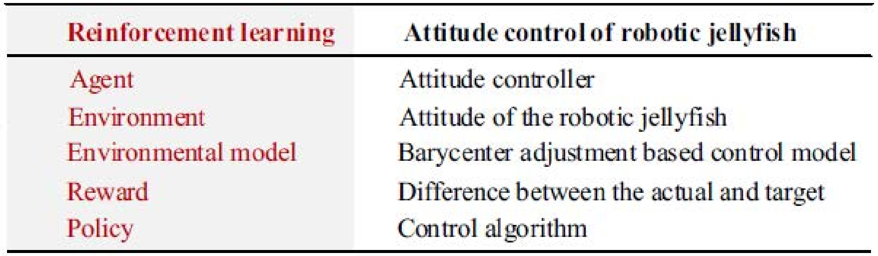
The state and corresponding policies taken by the robotic jellyfish

- Three propulsive behaviors, i.e., backward swimming, straight swimming, and turn



The corresponding elements of the RL based attitude control algorithm

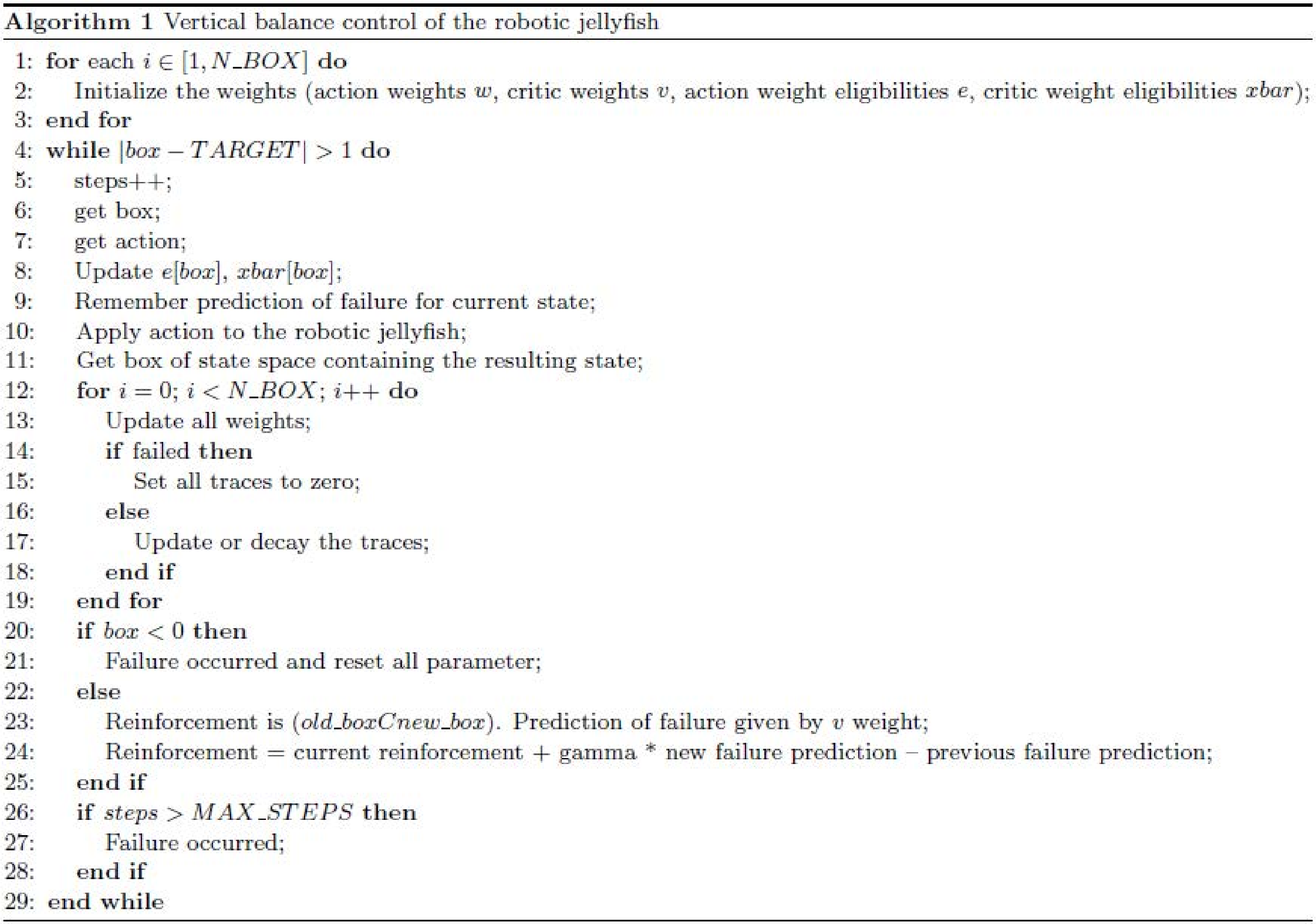




Reinforcement learning	Attitude control of robotic jellyfish
Agent	Attitude controller
Environment	Attitude of the robotic jellyfish
Environmental model	Barycenter adjustment based control model
Reward	Difference between the actual and target
Policy	Control algorithm

3. Reinforcement Learning Based Attitude Control

B. Attitude control



Algorithm 1 Vertical balance control of the robotic jellyfish

```
for each $i \in [1, N\_BOX]$ do
    Initialize the weights (action weights $w$, critic weights $v$, action weight eligibilities $e$, critic weight eligibilities $xbar$);
end for
while $|box - TARGET| > 1$ do
    steps++;
    get box;
    get action;
    Update $e[box]$, $xbar[box]$;
    Remember prediction of failure for current state;
    Apply action to the robotic jellyfish;
    Get box of state space containing the resulting state;
    for $i = 0$; $i < N\_BOX$; $i$++ do
        Update all weights;
        if failed then
            Set all traces to zero;
        else
            Update or decay the traces;
        end if
    end for
    if $box < 0$ then
        Failure occurred and reset all parameter;
    else
        Reinforcement is ($old\_boxCnew\_box$). Prediction of failure given by $v$ weight;
        Reinforcement = current reinforcement + gamma * new failure prediction – previous failure prediction;
    end if
    if $steps > MAX\_STEPS$ then
        Failure occurred;
    end if
end while
```

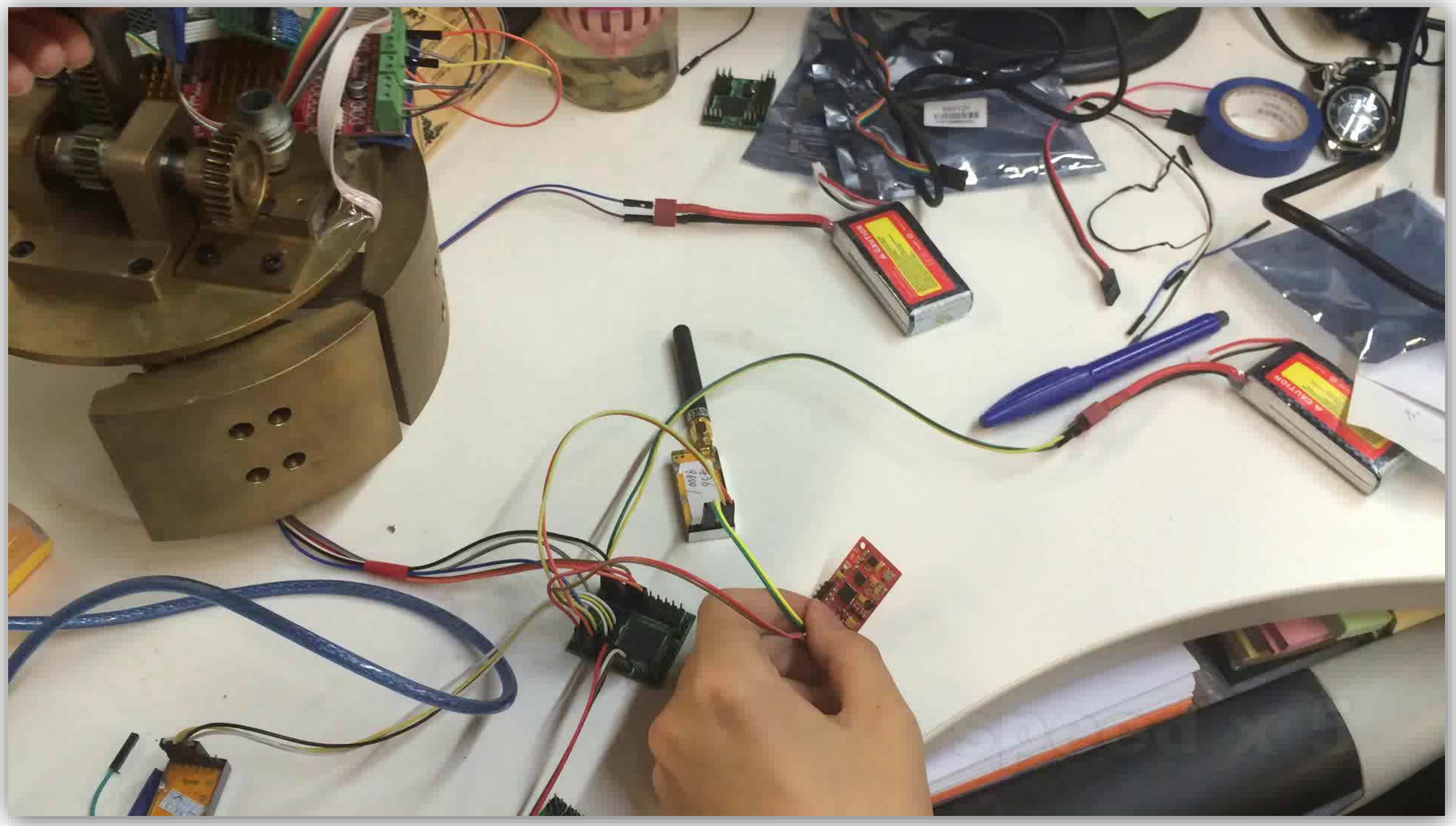
04 PART FOUR

Experiments and Results

4. Experiments and Results

A. Vertical balance attitude learning experiment

- The roll angle of the robot is invalid because of the symmetric structure.
- Yaw and pitch actions are employed to regulate spatial heading of the robot.

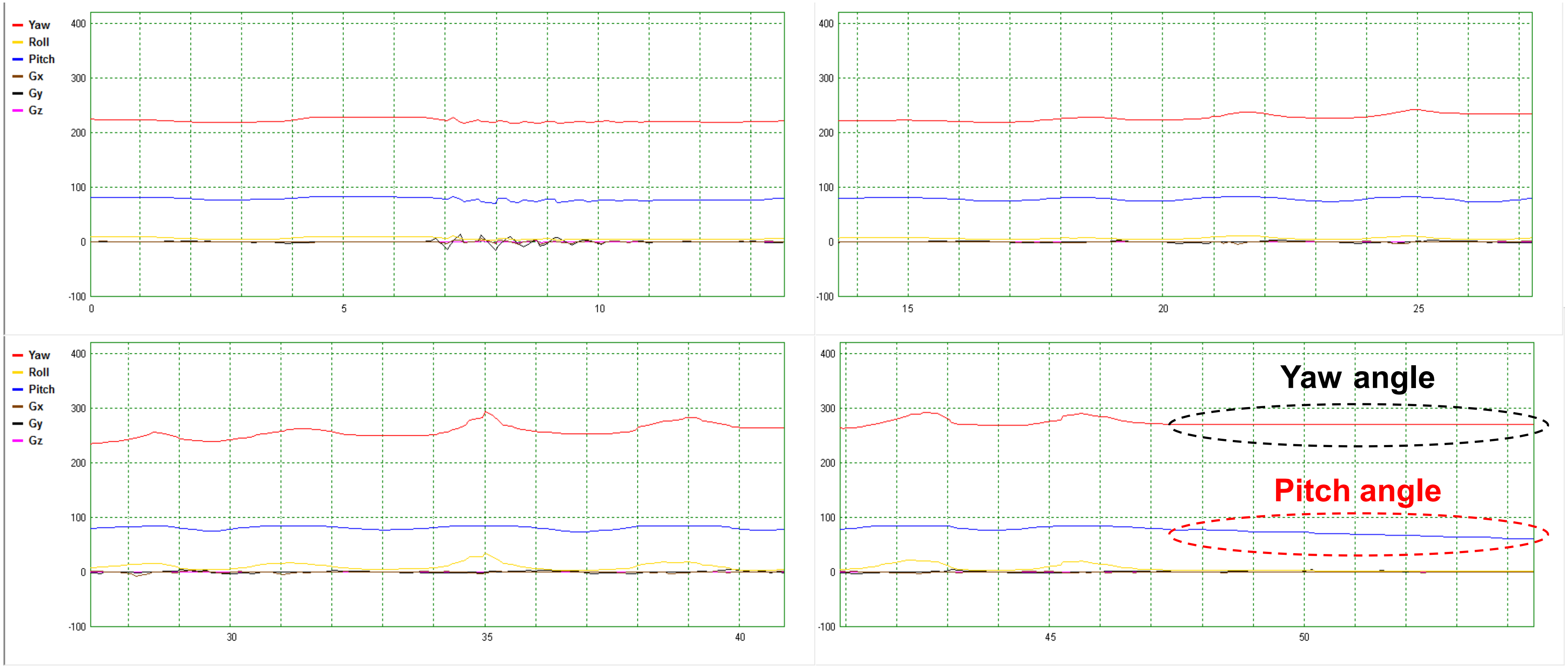


The vertical balance attitude learning process based on the Q-learning method

4. Experiments and Results

A. Vertical balance attitude learning experiment

- Given swimming attitude
  - Yaw angle: 280°
  - Pitch angle: 50°



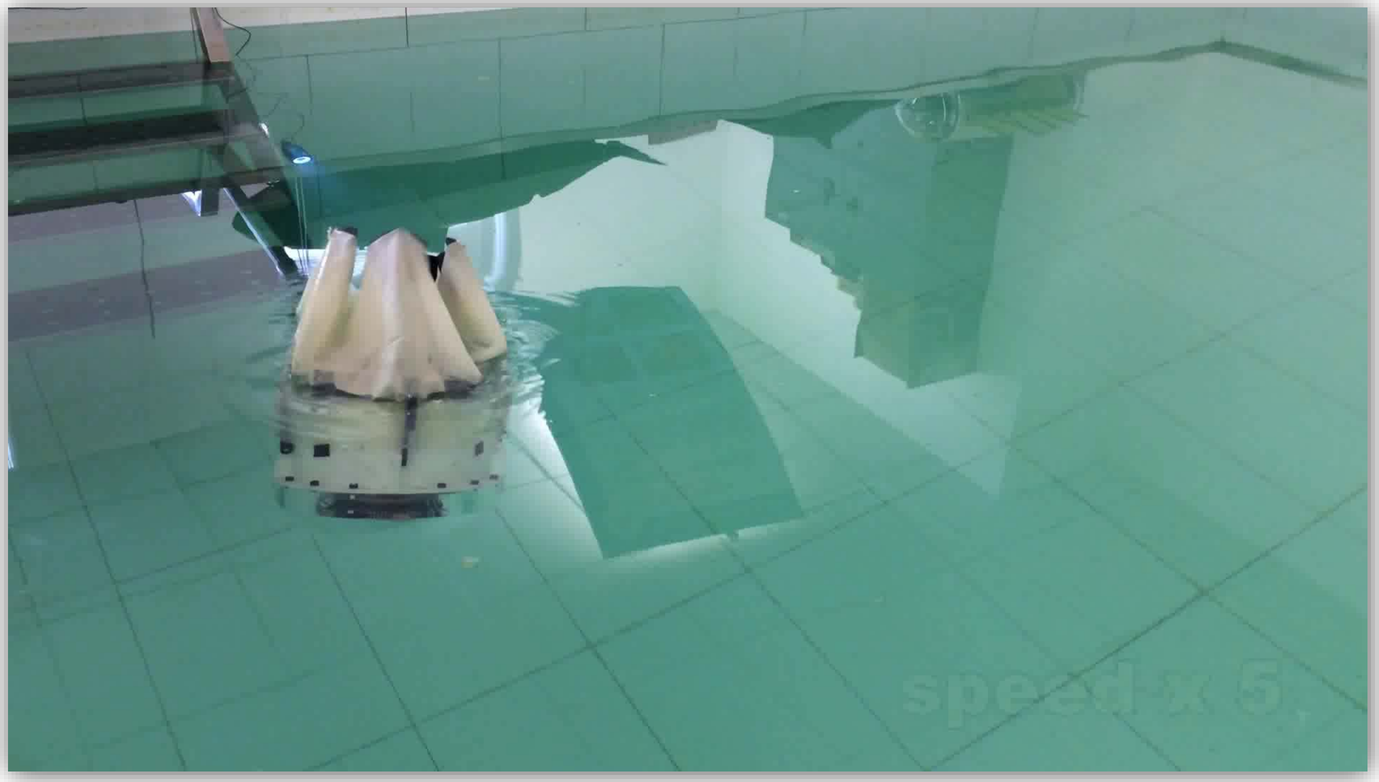
The attitude state of the robotic jellyfish during learning process

4. Experiments and Results

B. Hybrid motion experiment

- A series of dynamic angles including compound changes of the target yaw and pitch were set.

Swim down → Horizontal forward swimming → Horizontal turning motion

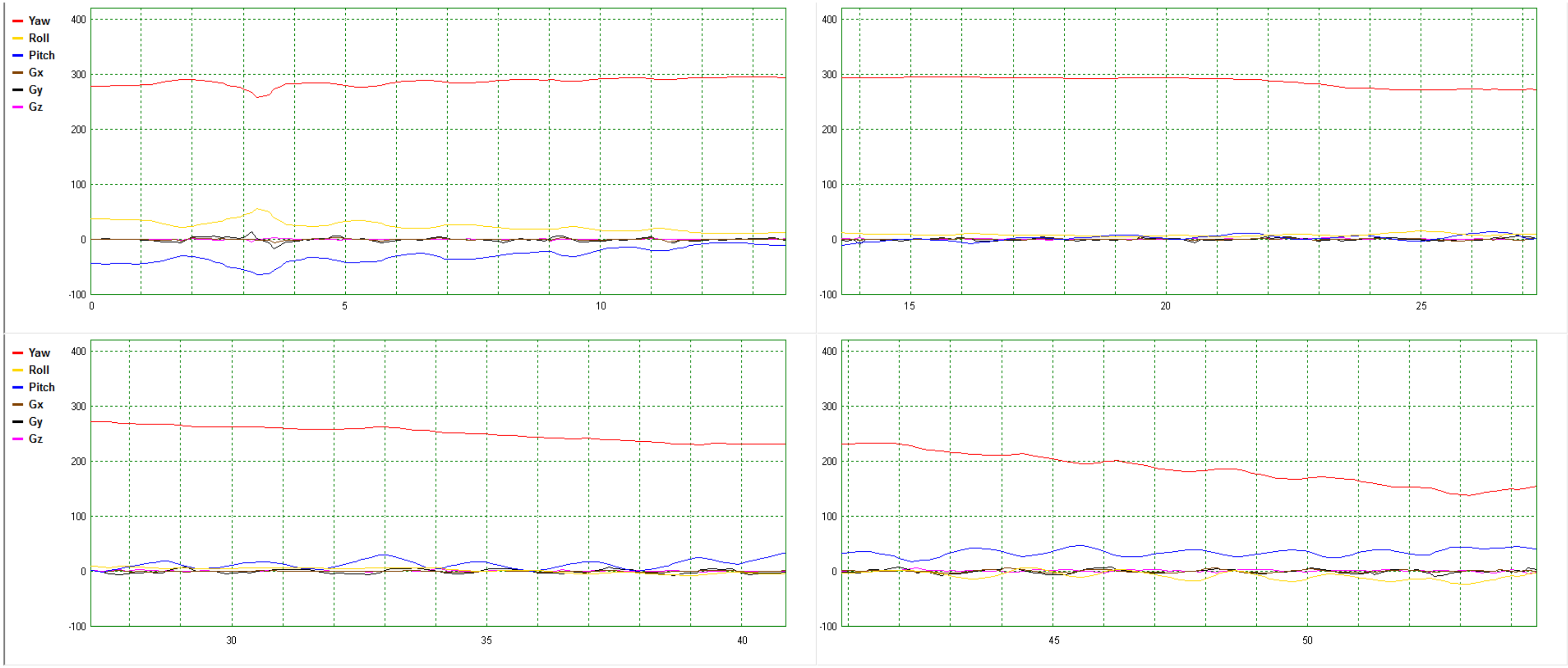


A hybrid motion interweaving vertical and horizontal swimming

4. Experiments and Results

B. Hybrid motion experiment

- Horizontal swimming speed: 100 mm/s
- Yaw turning speed: 5.6°/s
- Pitch turning speed: 3.6°/s



The attitude state in the hybrid motion experiment

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PART FIVE

Conclusion and Future Work

5. Conclusion and Future Work

A. Conclusion

1) A novel self-propelled robotic jellyfish based on the multi-linkage propulsive mechanism and barycenter adjustment mechanism is developed.

2) The proposal of a reinforcement learning based attitude control method makes the robotic jellyfish learn a desired attitude in 3D space.

3) Aquatic experiments verify the effectiveness of the presented mechanical design and attitude control method.

B. Future work

- ☐ More effort will focus on improving the attitude control method and the propulsive efficiency of the robotic jellyfish.

Thank you for your attention!