A Novel Active Tracking System for Robotic Fish Based on Cascade Control Structure

Xiang Yang, Zhengxing Wu, and Junzhi Yu

***Abstract*— This paper presents a novel active tracking control approach for a self-propelled robotic fish with onboard vision system. Considering the image instability caused by the swaying of the fish head, a camera stabilizer for visual system is designed to obtain stable images. Meanwhile, a feedback-feedforward controller is developed to maintain the attitude of camera to the inertial frame based on two Inertial Measurement Units (IMU) separately fixed on the camera and the fish body. In order to effectively track a target object, the Kernelized Correlation Filters (KCF) is adopted and a relevant active tracking controller is also designed. With the feedback-feedforward controller as an inner loop and the active tracking controller as an outer loop, a cascade control system is formed. Finally, the simulation and experiment results both verify the effectiveness of the mechanism design for the camera stabilizer and the corresponding cascade control approach for the active tracking system.**

I. INTRODUCTION

Robotic fish is a kind of underwater robot imitating the swimming action of real fish, which has acquired extremely high maneuverability and efficiency under water during the long time evolution. The MIT initiated the first research on robotic fish in 1994 [1]. Since then, a lot of researches have been conducted on robotic fish [2]–[6]. The excellent maneuverability and other features of robotic fish make it a commendable solution for some complex and hostile underwater missions [7], [8].

Camera, as a sensor with low cost yet rich information, is a perfect module for robotic fish system to accomplish complex mission. Yu *et al.* designed a robotic fish with ability to accomplish 3-D tracking control based on embedded vision system [9]. Wang *et al.* proposed a localization system for robotic fish using visual and inertial cues [10]. Compared with the matured applications in the ground, it is very hard to apply a camera in underwater robots. There are many challenges: 1) Lighting in the water is variable; 2) Ray of light is extremely out of uniformity; 3) Particulate confound noise model; 4) Communication between the underwater vehicles and the surveillance system is limited [12]; (5) Computing capability of embedded system is limited. For robotic fish, it is even more difficult since the swimming motion of fish inevitably causes swaying of camera, which might result in severe degeneration of image.

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The instability of image also causes problem for humanoid robot. Falotico *et al.* designed a model based on inverse kinematic controller to stabilize the pitch of humanoid robot head during walking [13]. Further, they proposed an adaptive model based on feedback error learning to overcome delays and to make the robot adapt to the dynamics of the head motion [14]. Some researches have focused on building actuator and mechanisms for robot eyes by mimicking the structure of human eyes [15]–[17]. Li *et al.* proposed a bionic control algorithm to ensure the stability of image from the camera [17]. Though their works are exciting, they do not fit to the small size robotic fish due to the limited space and limited computing power of it. Sun *et al.* have tried to reduce the swing of robotic fish head by optimizing the parameters of swimming motion [18]. This method is able to reduce the instability of image, but the speed of robotic fish has to be sacrificed. Doyle *et al.* adopted an algorithm based on optical flow to track a moving object with a real-time pan/tilt camera, which is used on Unmanned Aircraft System (UAS). The pan/tilt camera is simple, adaptable, but rather practical, which provides an important reference for designing a mechanism to stabilize the image.

The main purpose of this paper is to build a novel active tracking system for a robotic fish. In order to obtain stable images in fish swimming, a simple, compact and efficient camera stabilizer with a feedback-feedforward controller is designed. Based on the camera stabilizing system, the camera is modeled and a controller is designed to track the target object detected by the KCF algorithm. These two controllers form a cascade control system with camera stabilizing system as the inner loop and active tracking system as the outer loop. To verify the effectiveness of the control system, experiments have been conducted on the experimental platform. The results show that the camera stabilizing system can greatly reduce the instability of image and that the active tracking system can track the moving target object even with significant delay of image.

The rest of the paper is organized as follows. Mechanical design and dynamic model of camera stabilizer is given in Section II. A camera stabilizer controller is designed in Section III. Section IV details the camera model and the active tracking system. Experimental setup and corresponding results are given in Section V. Finally, the conclusions and future work are offered in SectionVI.

II. MECHANICAL DESIGN AND MODELING

The head of the robotic fish inevitably sways while swimming due to the counterforce on the swaying tail. The swaying of head causes severe distortion for the image captured by the camera loaded on the head. The distortion makes computer vision task a very difficult process.

The basic idea of this paper is to use rotary joints to keep the altitude angle of the camera stable to reduce the influence of the swaying of robotic fish head. Since the swaying of the robotic fish head is mainly along yaw axis and the space in the robotic fish is very limited, a one degree of freedom joint is sufficient and suitable for a small size robotic fish. The length of the robotic fish we designed is 480 mm. An extremely small motor (with gear reducer) whose size is 18.6 mm $\times$ 7.6 mm $\times$ 15.5 mm is adopted as the driving motor of the rotary joint, as shown in Fig. 1.

A simple model was built for the camera stabilizer in our previous work [22]. The transfer function of the controlled system is as follows:

$$\frac{\Theta(s)}{U_a(s)} = \frac{1}{as^3 + bs^2 + c} \tag{1}$$

where u_a is the equivalent voltage on the motor, θ is the altitude angle of the camera, and a, b, and c are parameters that can be obtained by system identification procedures.

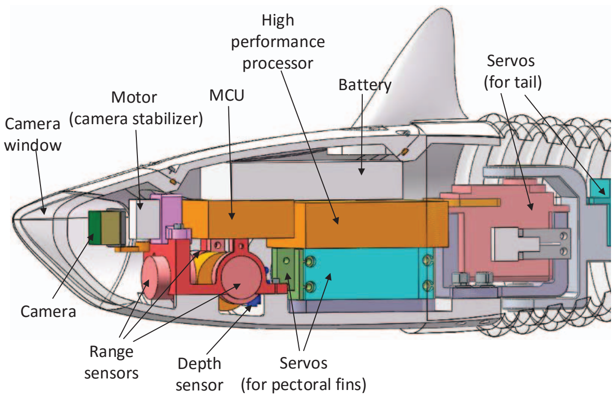

Fig. 1. Mechanical design of a robotic fish with a camera stabilizer.

III. Camera Stabilizing System

The swimming motion of robotic fish cause inevitable periodic yawing of the fish head. Generally speaking, the frequency of the Central Pattern Generator (CPG) output is set to 1–2 Hz, which means the head of robotic fish sways at the same frequency. The image of camera usually comes with latency, which is caused by a lot of factors including the exposure time, the analog to digital conversion time, the response latency of operating system and the time for visual tracking algorithm. The latency might be around 1 s, which is absolutely intolerable for the image that is shaking at a frequency of more than 1 Hz. There needs to be another way to fix the periodic yawing of the fish head.

In our previous work [22], a camera stabilizing system is proposed to keep the image stable while the fish head is yawing. The performance of the camera stabilizing system in simulation can be illustrated by Fig. 2 and Fig. 3. The camera stabilizing system can greatly reduce the instability of image and has good dynamic performance. The details of the camera stabilizing system can be referred to the paper [22].

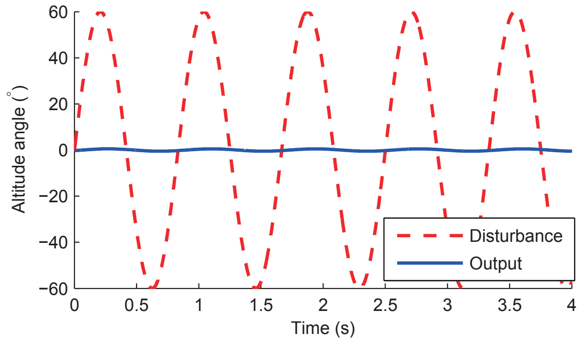

Fig. 2. Stable response of altitude angle with feedback-feedforward controller.

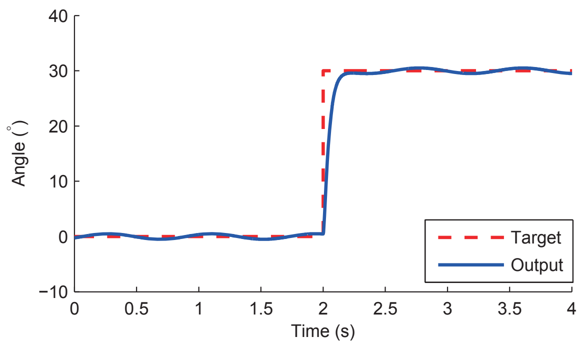

Fig. 3. Dynamic response of altitude angle with feedback-feedforward controller.

As can be seen from Fig. 3, it takes only about 0.2 s for the camera stabilizing system to reach the target angle, which is really fast concerning the scale of the image latency.

IV. Active Tracking System

With the camera stabilizing system, it is possible to assign a target yaw angle to the camera stabilizing system to track the target object. To control this system, a mathematical model between the yaw angle and the position of target object in image needs to be build.

According to [20], the geometric model of a camera (intrinsic parameters) could be described as follows:

$$\mathbf{p} = \frac{1}{z}\mathcal{M}\mathbf{P} \tag{2}$$

where $\mathbf{P} = (x, y, z, 1)^T$ denotes the vector of homogeneous coordinates of the point in the camera frame, $\mathbf{p} = (u, v, 1)^T$ is the homogeneous coordinates (in pixel units) of the corresponding point in the image frame, $\mathcal{M} = \begin{pmatrix} \mathcal{K} & 0 \end{pmatrix}$, and $\mathcal{K}$ is the intrinsic matrix of the camera, which is defined as (3).

$$\mathcal{K} = \begin{pmatrix} \alpha & -\alpha \cot\theta & c_x \\ 0 & \dfrac{\beta}{\sin\theta} & c_y \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

where θ is the angle between the two image axes, (c_x, c_y) is the position of the principal point in image, and α and β are the magnification coefficients indicating that a pixel will have dimensions $\dfrac{1}{\alpha} \times \dfrac{1}{\beta}$ in normalized image plane.

The target object is considered as a point for simplification. For most modern cameras, there is no skew issue, which means that θ should be 90° in general. Putting them all together, it yields:

$$\mathbf{p} = \frac{1}{z} \begin{pmatrix} \alpha & 0 & c_x & 0 \\ 0 & \beta & c_y & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \mathbf{P} \tag{4}$$

According to (4), it follows that:

$$\begin{cases} u = \alpha \dfrac{x}{z} + c_x \\ v = \beta \dfrac{y}{z} + c_y \end{cases} \tag{5}$$

If the camera rotates angle ϕ about y-axis of the camera frame A, the camera frame after the rotation is denoted as frame B, as shown in Fig. 4.

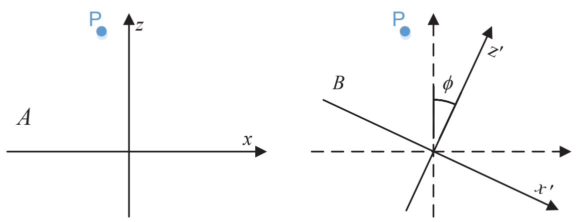

Fig. 4. The change of camera frame after a rotation about y-axis.

It is easy to get the rotation matrix from frame A to frame B:

$$^{A}_{B}\mathbf{R} = Rot\,(y, \phi) \tag{6}$$

$\mathbf{P}$ is a point in frame A, and its coordinates in frame A is:

$$^{A}\mathbf{P} = (x_0, y_0, z_0)^T \tag{7}$$

Its coordinates in frame B $^{B}\mathbf{P} = ({x_0}', {y_0}', {z_0}')^T$ could be obtained by following formula:

$$\begin{aligned} ^{B}\mathbf{P} &= {^{B}_{A}\mathbf{R}}\,{^{A}\mathbf{P}} = {^{A}_{B}\mathbf{R}^{-1}}\,{^{A}\mathbf{P}} \\ &= \begin{bmatrix} x_0 \cos\phi - z_0 \sin\phi \\ y \\ x_0 \sin\phi + z_0 \cos\phi \end{bmatrix} \end{aligned} \tag{8}$$

According to (8) and the fact that origin position of the tracking object is in the center of the image, which means the x_0 in $^{A}\mathbf{P}$ is 0, we obtain:

$$\begin{cases} {x_0}' = -z_0 \sin\phi \\ {z_0}' = z_0 \cos\phi \end{cases} \tag{9}$$

The image coordinates (x-axis only) of $^{A}\mathbf{P}$ and $^{B}\mathbf{P}$ can be obtained by combining (5), (7) and (9):

$$\begin{cases} u_0 = \alpha \dfrac{x_0}{z_0} + c_x = c_x \\ {u_0}' = \alpha \dfrac{{x_0}'}{{z_0}'} + c_x = -\alpha \tan\phi + c_x \end{cases} \tag{10}$$

According to (10), the mathematical model of the relationship between yaw angle ϕ and the x-axis coordinate u in image is describe by following formula:

$$u = -\alpha \tan\phi + c_x \tag{11}$$

The intrinsic parameters could be obtained by camera calibration [20]. For our camera, its intrinsic matrix is:

$$\mathcal{M} = \begin{bmatrix} 686.77 & 0 & 354.92 \\ 0 & 708.49 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12}$$

which is obtained by MATLAB Camera Calibrator Toolbox.

If the input is yaw angle and the output is pixel coordinate, the controlled system could be described as the following block diagram, see Fig. 5.

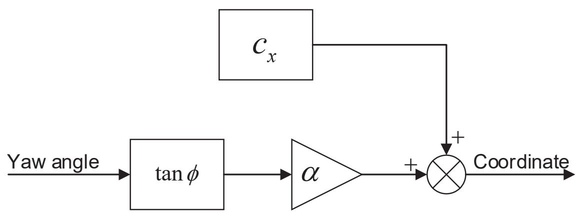

Fig. 5. Block diagram of the image tracking controlled system.

This is a very simple non-linear system. The derivation of u is:

$$\frac{du}{dt} = \alpha \frac{1}{\cos^2\phi} \tag{13}$$

Since the input yaw angle is usually around 0, the system could be linearized to the following form:

$$u = \left.\frac{du}{dt}\right|_{\phi=0} u + c_x = \alpha u + c_x \tag{14}$$

So the transfer function of the linearized controlled system becomes:

$$G_l\,(s) = \alpha \tag{15}$$

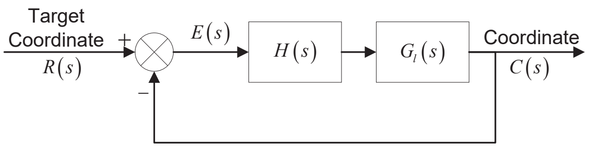

Fig. 6. Block diagram of the linearized image tracking control system.

A feedback controller $H(s)$ is designed to control the system $G_l(s)$. The block diagram of the closed-loop control system is shown in Fig. 6.

The closed-loop transfer function of the control system is:

$$\frac{R(s)}{C(s)} = \frac{H(s)G_l(s)}{1+H(s)G_l(s)} \tag{16}$$

Considering the steady state error of the system, we can obtain the error between the target coordinate and the measured coordinate:

$$E(s) = R(s) - C(s) = \frac{R(s)}{H(s)G_l(s)} \tag{17}$$

When the input is a step signal, i.e., $R(s) = \frac{1}{s}$, the steady state error e_{ss} of the system could be obtained by following formula:

$$e_{ss} = \lim_{s\to 0} sE(s) = \frac{1}{\alpha \lim\limits_{s\to 0} H(s)} \tag{18}$$

To ensure $e_{ss} = 0$, we can make $H(s) = \frac{1}{K_p s}$, i.e., a simple integrator.

Another issue needed to be considered is the severe latency of the sensor. To avoid getting the system unstable, moderate control strategy should be adopted, which means an appropriate K_p parameter is required.

Putting the camera stabilizing system and the active tracking system together, we can get the block diagram of the whole control system, as shown in Fig. 7.

The disturbances are set as:

$$n_1(t) = \frac{\pi}{6}\sin(2\pi t) \quad t \in (0, +\infty) \tag{19}$$

$$n_2(t) = \begin{cases} 0 & t \in (0,5) \\ 200(t-5) & t \in (5,7) \\ 400 & t \in (7,+\infty) \end{cases} \tag{20}$$

The latency of sensor is set as $t_{sl} = 0.4$, and the K_p in $H(s)$ is set as $K_p = 0.0016$.

The output of this system in simulation is shown in Fig. 8.

With a disturbance which is a ramp signal with slope of 200 pixel per second, the controller can keep the output error $|e_{ss}| < 200$, which indicates that this controller is an effective controller for tracking an object in image.

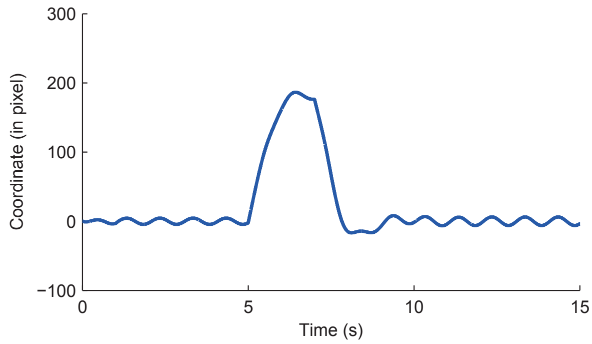

Fig. 8. The block diagram of the linearized image tracking control system.

V. Experiments

An experimental platform is built to verify the effectiveness of the design of active tracking system in this paper, which is shown in Fig. 9.

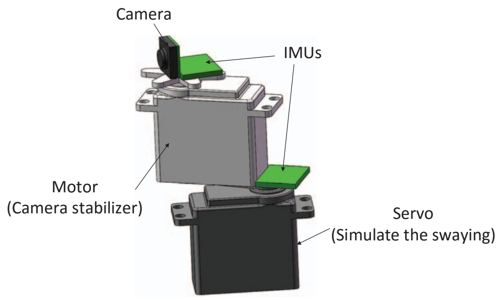

Fig. 9. The built experimental platform.

The camera is loaded on the upper motor, which acts as the camera stabilizer. The lower servo is used to simulate the swaying of the fish head. There are two IMUs in the system, one is mounted on the camera and another is mounted on the camera stabilizer.

A sine wave with 1 Hz frequency and $\pi/6$ amplitude is set as the disturbance of the camera stabilizing system, and the result is shown in Fig. 10 shows. The amplitude of the output is approximately 6°, which is only one fifth of the disturbance. The result might not be as good as the simulation shows due to the simplification of the model of the controlled system, but it is sufficient for active tracking system to get a clear image.

A step signal with $\pi/6$ amplitude is set as the target angle of the camera stabilizing system with disturbance on it. The result of the experiment is shown in Fig. 11. As can be seen from the response curve of the output yaw angle, it only takes around 0.1 s to reach the target altitude angle. However, considering that the disturbance might accelerate the process of reaching the target depending on the phase of the disturbance, it is more appropriate to consider the time that it takes to follow the waveform of the output without the step signal. Thus, the response time of the camera stabilizing

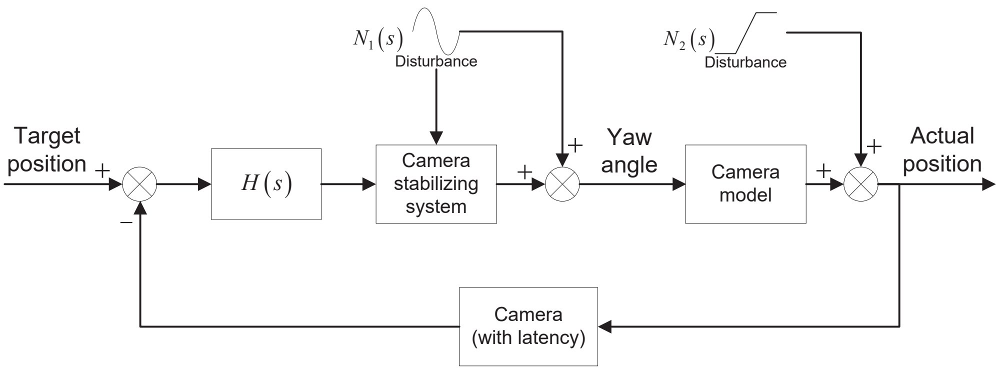

Fig. 7. Block diagram of the image tracking control system with camera stabilizing system.

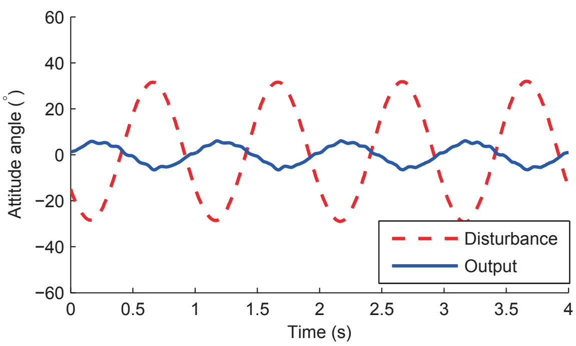

Fig. 10. Output yaw angle of camera stabilizing system with disturbance.

system for the step input signal is around 0.2 s, which is very close to the result of simulation.

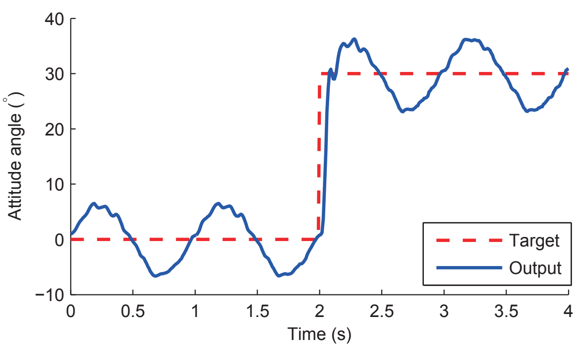

Fig. 11. Step response of camera stabilizing system with disturbance.

To carry out the experiments of tracking an object in image, it is important to be able to replicate the movement of the object exactly the same every time. It is also very import to control the trajectory and time of the movement. Considering those requirements, it is convenient and feasible to use a moving object on a screen to simulate the movement of a real object. The schematic diagram of experiment environment is shown in Fig. 12.

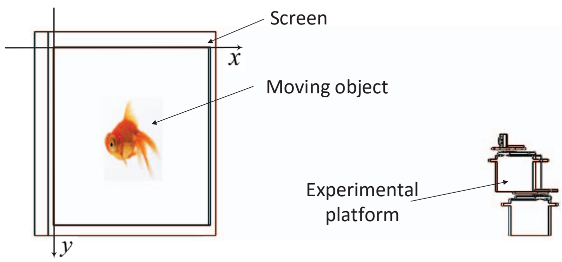

Fig. 12. Experiment environment.

The object on the screen moves along the x-axis. Coordinate of the object on x-axis of the image frame changes 400 pixels in 2 s during its movement, which is the ramp signal $N_s(s)$ in Fig. 7. $N_1(s)$ is set as a sine wave with 1 Hz frequency and $\pi/6$ amplitude. The phase difference between $N_1(s)$ and $N_s(s)$, which is not important, is not set in the experiment. The tracking algorithm used to track the target object is KCF [23], which has remarkable performance while low computation cost and is very suitable for embedded system of robotic fish.

These experiment settings yield waveform of target coordinates in image shown in Fig. 13. The maximum error of coordinate in the experiment is 230 pixels, which is very close to 186 pixels in simulation. It takes about 4 s to regain a stable sine waveform in the experiment, which is exactly the same as the time it takes in simulation.

The images captured by the camera is listed in Fig. 14. The target object never escapes the view of camera. The blurring of image is low. The algorithm works well and the target object is correctly detected during the whole process. Fig. 14 is a strong proof for the effectiveness of the active tracking system this paper proposes.

VI. Conclusions and Future Work

This paper has proposed a cascade control system for a robotic fish to track a target object through developing

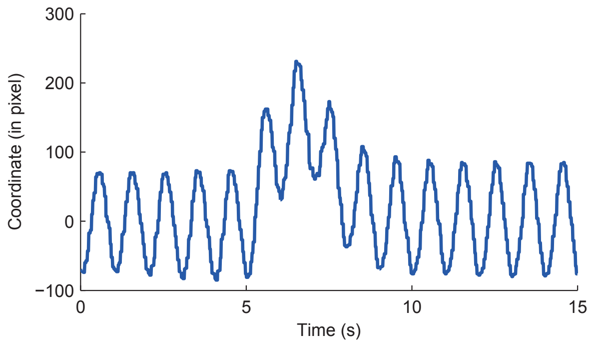

Fig. 13. Tracking error of active tracking system.

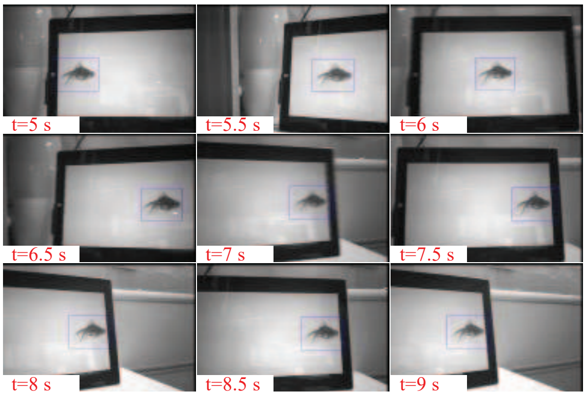

Fig. 14. Images captured during the tracking process.

a camera stabilizer as the inner loop and a image based tracking system as the outer loop. Specifically, to get a stable image, the inner loop with a feedbak-feedforward controller stabilizes the altitude angle of camera, which has periodic disturbance due to the swaying of robotic fish head. Meanwhile, the outer loop tracks the object detected by the visual tracking algorithm through setting the altitude angle of the inner loop. Taking latency of sensors into consideration, the whole control system shows good tracking performance in simulation. For the purpose of verifying the proposed control system, an experimental platform is developed to simulate the swaying of fish body. The experiment results demonstrate that the camera stabilizer can significantly reduce the blurring of image, and that the cascade control system is stable and effective for tracking a moving object.

The ongoing and future work will focus on the application of this active tracking system in a real robotic fish and further optimizing its performance according to the problem encounters in the real robotic fish. With the high quality visual tracking information of target object obtained by the proposed active tracking system, it is necessary to investigate the proper algorithm for approaching the target object.

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