

Emergence of Robotic Intelligence by Chaos for Catching Fish

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Abstract: In this paper we tackle a Fish-Catching task under a visual feedback hand-eye robotic system with a catching net. Taken into consideration of emotional aspect, the fish can suddenly change its escaping trajectory or speed up when being threatened as the net attached at hand approaches to it. As the time of tracking and catching process flows, the fish can somewhat get accustomed to the net motion pattern and gradually find out new strategies on how to escape from the bothering net. For the sake of such innate ability being widely existed in animal behavior, the catching operation becomes tough and some effective intelligent method needs to be conceived to go beyond the fish intelligence. The purpose of this paper is to construct intelligent system to be able to exceed the fish intelligence in order to track and catch the fish successfully. Then we embed chaotic motion into the net motion to realize a kind of robotic intelligence, and we have shown the chaotic net motion can overcome the fish escaping strategies.

Keywords: Chaos, Intelligent, Gazing GA

1. INTRODUCTION

In recent years, visual tracking and servoing in which visual information is used to direct the end-effector of a manipulator toward a target object has been studied in some researches [1],[2]. A new trend of machine intelligence [3] that differs from the classical AI has been applied intensively to the field of robotics and other research areas like intelligent control system. Typically, the animal world has been used conceptually by roboticians as a source of inspiration for machine intelligence. For the purpose of studying animal behavior and intelligence, the model of interaction between animals and machines is proposed in researches like [4]. In our previous research, the fish emotional behavior has also been examined and the robot with adaptive ability to react to the fish status is conceived. In these days, the technique about hierarchical organized control hardware and the multilevel multisensor based on fusion technique to obtain fused decisions has been described in [5], so the intelligent information fusion and judgment can be available through the fusion technique. Another crucial characteristic of machine intelligence is that the robot should be able to use input information from sensor to know how to behave in a changing environment and furthermore can learn from the environment for safety like avoiding obstacle. Behavior acquisition has been achieved and the simulated robot can learn to follow a light and to avoid hot dangerous objects shown in [7]. As known universally that the robot intelligence has reached a relatively high level, still the word intelligence is an abstract term, so the measurement of the intelligence level of a robot has become necessary. A practical and systematic strategy for measuring machine intelligence quotient (*MIQ*) of human-machine cooperative systems is proposed in [6].

In our system, we will evaluate the intelligence degree between fishes and the robot by the result of Fish-Catching. We can declare that the system combined with

chaos be smarter than the fish when the robot can beat the fish by catching it successfully even after the fish finds out some escaping strategy. As we did not find the research about the intelligence completion between animal and robot, we mainly dedicate ourselves to constructing a smart system that is more intelligent than the fish. We consider that the competitive relation can be very meaningful as one way to discuss robotic intelligence. So we not only employ the inspiration of animal behavior for robot intellectualization, we can also conceive a robot that can exceed the animal intelligence. By evolutionary algorithms [8], Visual Servoing and Object Recognizing based on the input image from a CCD camera mounted on the manipulator has been studied in our laboratory [9], and we succeeded in catching a fish by a net attached at the hand of the manipulator based on the real-time visual recognition under the method of Gazing GA [10] to enhance the real-time searching ability.

We have learned that it is not effective for fish catching to simply pursue the current fish position by visual servoing with velocity feedback control. Actually, the effective tracking can be impossible because the fish can sometimes alter motion pattern suddenly under some emotional reasons of fear or the fish can take some strategy to try to get rid of the bothering net that keeps chasing it. Those behaviors are thought to be caused by emotional factors and they can also be treated as a kind of innate fish intelligence, even though not in a high level. Based on the fish behavior observation in the real Fish-Catching experiment, the fish mostly swims stick to the pool edge for avoiding the net after being caught for a while. That is a serious problem for the Fish-Catching task because when the fish only swims in the corner it is prohibited for the net to enter into the corner for Fish-Catching operation. That shows the system is not intelligent enough, so effective method is expected to be conceived in order to cope with the fish escaping strategy. While observing the fishes' adapting behavior to escape in the competitive

relations with the robot, we found that we can define a ‘‘Fish’s Intelligent Quotient’’(FIQ) representing decreasing velocity of fish number caught by the net. Through this measure we will compare the innate intelligence of the fish and the artificial intelligence of the robot.

In this paper we adopt the chaos model obtained from signal transfer in cell structure [11],[12]. We embed chaos into the Robot Dynamics in order to supplement the deficiency of our Fish-Catching system, because intelligent composite motion control [13] becomes crucial in the catching fish process. The Chaotic motion will be added to increase the possibility of catching fish according to the fish motion state and we can call that motion adaptive ability that is being researched in our lab [14]. We improved the system performance by the combination of N.N. prediction and chaotic motion to conceive a kind of idea with probabilistic chaotic motion, in other words we have tried a new strategy to make the system smart enough to exceed the fish intelligence.

2. RANDOM AND CHAOS

A random number is unpredictable. It seems that it is impossible to express the random number by computer program, because computer program is just able to output a sequence of number by prescribed programs, resulting in the output number be essentially predictable. Actually, the random number generation routine in computer is called pseudorandom number, it is not real random number with genuine unpredictability. That means the pseudorandom number is predictable. A function to generate a ‘‘random number’’ prepared in a standard language like ‘‘C++’’ is based on the linear congruential method almost without exception, producing pseudorandom number of cyclic oscillation with huge cycle. This method is proposed by Lehmer, D.H. around 1948, and it’s so easy and efficient for generating pseudorandom-numbers, named ‘‘linear congruential method’’ with the following recurrence formula [15].

$$X_n = aX_{n-1} + c \pmod{M}, n \geq 1 \quad (1)$$

This equation can output integer pseudorandom-numbers sequence X_0, X_1, X_2, \dots . The M is called modulus of congruence expression. a and c are positive integer. a is called multiplier, c is called increment. So, the remainder value, coming from $aX_{n-1} + c$ divide by M , is set to X_n . In eq.(1) there is a period, this period is no larger than M . If M , a , and c are chosen well combination, the maximum cycle M can be obtained. In the case of the maximum period, all the integer numbers not smaller than 0 and not larger than $M - 1$ appear in somewhere. No matter X_0 , it becomes the same sequence of numbers after all only by a sequence of numbers beginning from there, and this is a periodic function.

Chaos has the character of unpredictability. This happens by negligible differences of initial positions bear unpredictable huge difference between the solved trajectories. This means that deterministic equation of chaos can generate unpredictability. The Bernoulli shift is mentioned as a typical example that realizes the character of

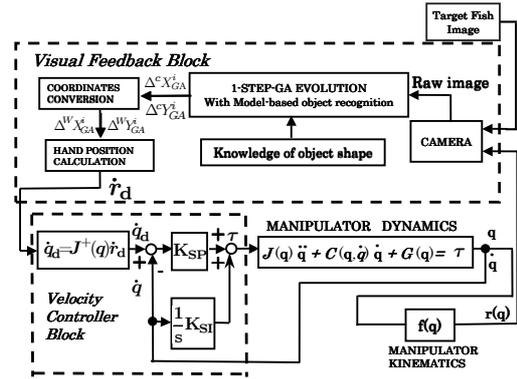


Fig. 1 Block diagram of the controller

the chaos. The Bernoulli shift is expressed by considering the variable X_i is a real number and by substituting $a = 2, c = 0, M = 1$ into eq.(1).

$$X_n = 2X_{n-1} \pmod{1}, n \geq 1 \quad (2)$$

That is, chaos and pseudorandom numbers can be generated by the same equation. As mentioned above, we consider that chaos and random numbers have relations of intersection.

3. FISH TRACKING AND CATCHING

The problem of recognition of a fish and detection of its position/orientation is converted to a searching problem of $x(t), y(t)$ in order to maximize $F(\phi(x(t), y(t)))$, where $\phi(x(t), y(t))$ represents correlation function of a new image and matching model to a fish at time t . $F(\phi(t))$ is used as a fitness function of GA [10]. To recognize a target in a dynamic image input by video rate, 33 [fps], the recognition system must have real-time nature, that is, the searching model must converge to the fish in the successively input raw images. An evolutionary recognition process for dynamic images is realized by such method whose model-based matching by evolving process in GA is applied at least only one time to one raw image input successively by video rate. We named it as ‘‘1-Step GA’’ [9]. When the converging speed of the model to the target in the dynamic images should be faster than the swimming speed of the fish in the dynamic images, then the position indicated by the highest genes represent the fish’s position in the successively input images in real-time. We have confirmed that the above time-variant optimization problem to solve $\phi(t)$ maximizing $F(\phi(t))$ could be solved by ‘‘1-Step GA’’. We employed the combined method, which utilizes both the global search and the local search techniques of a GA, to perform a tracking and catching experiment of a swimming fish by using the experimental system depicted as a block diagram shown in Fig.1. The camera-to-fish distance is 450 [mm]. The size of the water pool is 300 (width) \times 400 (length) \times 100 (depth) [mm], and the net is 80 \times 100 [mm]. Catching the fish is executed by pulling up the net when the fish is within an area of 86 \times 66 [mm]

at the center of the net attached at the robot hand and detected by a hand-eye CCD camera at the center of image view.

The aforementioned real-time recognition system using the shape of the fish as the knowledge base is depicted in the upper side of the block diagram in Fig.1. In the figure, $\Delta \mathbf{r} = [\Delta^W X_{GA}^i, \Delta^W Y_{GA}^i]$ is the X-Y deviation from the camera center to the fish expressed in the world coordinates, and the camera center also stands for the center of the catching net. The desired hand velocity at the i -th control period $\dot{\mathbf{r}}_d^i$ is calculated as

$$\dot{\mathbf{r}}_d^i = \mathbf{K}_P \Delta \mathbf{r}^i + \mathbf{K}_V (\Delta \mathbf{r}^i - \Delta \mathbf{r}^{i-1}) \quad (3)$$

where $\Delta \mathbf{r}^i$ denotes the net current position vector from the camera center to the fish position observed in real time by 1-Step GA [9]. \mathbf{K}_P and \mathbf{K}_V given are positive definite matrix to determine PD gain. Now we add chaos and N.N. items to eq.(3) above, and we also need to redefine the meaning of $\dot{\mathbf{r}}_d^i$.

Here \mathbf{r}_d^i designates the place robot hand should move towards. In order to determine the net destination, we think it is necessary to consider the fish motion state. Based on the fish current position, velocity and recognition result, two kinds of motion pattern can be taken and those are shown below. When the fish is recognized successfully, the net mounted at hand will chase the fish directly and $\Delta \mathbf{r}_{fish}^i$ denotes the recognized fish position deviation vector from the net center to the fish within the camera frame. When the fish stays in a corner of the pool, the net will do chaotic motion automatically and $\Delta \mathbf{r}_{chaos}^i$ denotes the vector towards the next point in chaotic trajectory. Therefore the new definition of $\Delta \mathbf{r}^i$ arisen in eq.(3) right side is shown as below:

$$\Delta \mathbf{r}^i = k_1 \cdot \Delta \mathbf{r}_{fish}^i + k_2 \cdot \Delta \mathbf{r}_{chaos}^i \quad (4)$$

Here $\Delta \mathbf{r}_{fish}^i = [\Delta x_{fish}^i, \Delta y_{fish}^i]$, and $\Delta \mathbf{r}_{chaos}^i = [\Delta x_{chaos}^i, \Delta y_{chaos}^i]$. Therefore the hand motion pattern can be determined by the switch value k_1 and k_2 . $k_1 = 1$ and $k_2 = 0$ indicate the motion command signal to net is to track the fish and $\Delta \mathbf{r}_{fish}^i$ denotes the vector from the camera center to the fish position in the camera frame. $k_1 = 0$ and $k_2 = 1$ indicate the net will do chaotic motion under certain condition satisfied either to lure the fish to come out of the corner or threaten the fish. The desired joint variable $\dot{\mathbf{q}}_d$ is determined by inverse kinematics from $\dot{\mathbf{r}}_d$ by using the Jacobian matrix $\mathbf{J}(\mathbf{q})$, and is expressed by

$$\dot{\mathbf{q}}_d = \mathbf{J}^+(\mathbf{q}) \dot{\mathbf{r}}_d \quad (5)$$

where $\mathbf{J}^+(\mathbf{q})$ is the pseudoinverse matrix of $\mathbf{J}(\mathbf{q})$. The robot used in this experimental system is a 7-Link manipulator, Mitsubishi Heavy Industries PA-10 robot. The control system, based on a PI control of PA-10 is expressed as

$$\boldsymbol{\tau} = \mathbf{K}_{SP}(\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) + \mathbf{K}_{SI} \int_0^t (\dot{\mathbf{q}}_d - \dot{\mathbf{q}}) dt \quad (6)$$

where $\dot{\mathbf{q}}_d - \dot{\mathbf{q}}$ is the velocity error of the joint angle, \mathbf{K}_{SP} and \mathbf{K}_{SI} are symmetric positive definite matrices to determine PI gain. The orientation of the fish is measured

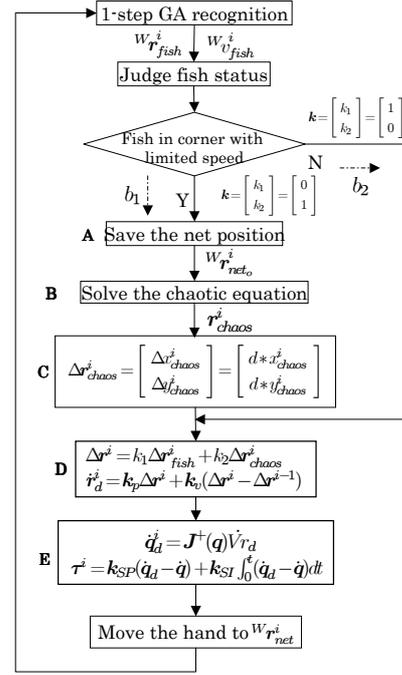


Fig. 2 Intelligent motion composite process

in real time, but in the tracking and catching experiment, the measured orientation information is not used for the orientation control of the net as shown in the above equation. The manipulator servo update rate is 100[Hz].

In order to describe the details of the dynamical control flow, we show the intelligent motion composite process in Fig.2. By 1-step GA recognition method [9], the fish position and velocity information can be available, with which the fish status can be judged in real time. When the condition of fish being in corner with a certain limited speed satisfied, the motion control process enters into b_1 branch with $k_1 = 0, k_2 = 1$, otherwise enters into b_2 branch with $k_1 = 1, k_2 = 0$, which determine the net motion type shown in eq.(4). Before chaotic motion taken in b_1 branch, the current net position must be saved in advance for next net position calculation in eq.(7). The chaos equation eq.(13) is solved shown in block B. Then we set the saved net position as the new origin of chaotic motion. The chaotic motion coordinate in camera frame is calculated as in block C, where d is a coefficient with a value of 18 and can be regulated based on the vertical distance between camera and the pool. Then by the kinematics calculation process shown in block D and E, we can finally get the $\boldsymbol{\tau}^i$ of each joint of the manipulator. At last the hand is made to move to $W \mathbf{r}_{net}^i$, which is the net position in world frame and can be calculated as follow:

$$\begin{aligned} W \mathbf{r}_{net}^i &= \begin{bmatrix} W x_{net}^i \\ W y_{net}^i \end{bmatrix} \\ &= \begin{bmatrix} W x_{net_o}^i \\ W y_{net_o}^i \end{bmatrix} + \Delta \mathbf{r}^i \end{aligned} \quad (7)$$

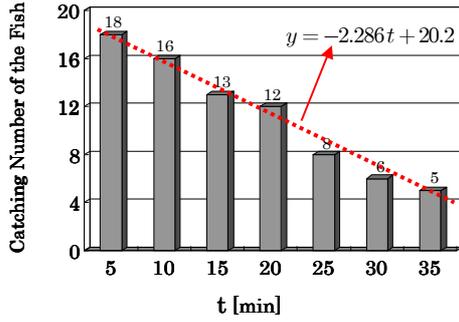
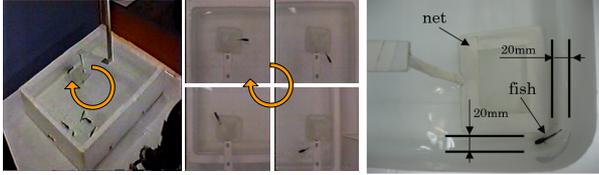


Fig. 3 Result of catching number



(a) Motion (1) of a fish

(b) Motion (2) of a fish

Fig. 4 Fish motion

4. PROBLEM OF FISH-CATCHING

In order to check the system reliability in tracking and catching process, we kept catching several fishes continuously for 35 minutes with condition of $k_1 = 1$ and $k_2 = 0$ through out this experiment. We released 8 fishes (length is about 40[mm]) in the pool in advance, and once the fish got caught it would be released to the same pool at once. The result of this experiment is shown in Fig.3, in which vertical axis represents the number of fishes caught in successive 5 minutes and horizontal axis represents the catching time. We had expected that the capturing operation would become smoother as time flew on consideration that the fish may get tired. But to our astonishment, the number of fishes caught decreased gradually.

The reason of decreased catching number lies in the fish learning ability or emotional factor stated before. For example, the fish could learn how to run away around the net shown in Fig.4(a) by circular motion with keeping constant distance from the net. Also, the fish can keep staying within the clearance between the edge of the pool and the net shown in Fig.4(b) where it is prohibited for the net to enter. To evaluate numerically how fast the fish can learn to escape the net, we adapted Linear Least-Square approximation to the fish-catching decreasing tendency, resulting in $y = -2.286t + 20.2$ as shown in Fig.3. The decreasing coefficient -2.286 represents adapting or learning velocity of the fishes as a group when the fishes' intelligence is evaluated based on robotic performance given as a standard. We named the coefficient as "Fish's Intelligence Quotient"(FIQ). The larger minus value means high intelligence quotient, zero does equal, and plus does less intelligence than robot's.

To overcome the fishes' intelligence, more intelligent robotic system needs to track and catch the fish effectively, in other words it comes to the problem on how to use the item Δr_{chaos}^i in eq.(4) effectively to exceed the fish intelligence.

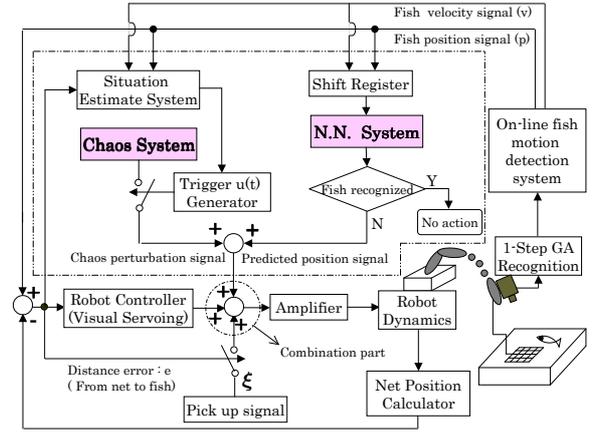


Fig. 5 The proposed system flow

5. THE PROPOSED SYSTEM

Within the dotted line part in Fig.5 there are newly proposed chaos that are used to increase the intelligent degree of the whole system. When the preset conditions are satisfied, the chaos motion result will be combined and input into the Visual Servoing System. As mentioned before, when the fish motion is affected by emotional factor or the fish conceives new strategy to avoid being caught by net, reliable tracking and catching operation to overcome the adaptive ability can become impossible without new machine adaptation going beyond the fish strategies.

Let us pay attention to the details of the proposed system flowchart in Fig.5 including a generator of chaos to make this system possess a kind of idea of tracking motion of the net. The CCD camera acting as hand-eye is mounted on the manipulator and the block of 1-Step GA Recognition is used to perform recognizing the fish after hand-eye taking the image into the recognition block every 33ms. Then according to the recognized result, the next block called On-Line Fish Motion Detection System can deduce fish position and velocity information and after this there are two data channels that contain fish position and velocity signals respectively. First these signals flow into Shift Register that restores history data for preparation of N.N. future motion prediction use. Also the position and velocity signals flow into another branch in which there exists top block called Situation Estimate System used to estimate the fish motion state based on the value of position, velocity and distance error. In other words, that block is used to judge conditions like the fish speeding up suddenly, staying within a corner or keeping a constant distance against the net. Also in the same branch the Chaos System is used to generate chaos motion trajectory and Trigger $u(t)$ Generator is used to control the degree of chaos influence to the net motion. The data branch that only contains position signal is also used to regulate the net position by comparing its value with fish real position. Then the distance error can be obtained and it flows into Robot Controller that sends control signal to Amplifier. Finally, the Robot Dynamics block performs manipulator motion control based on the inputting control signal.

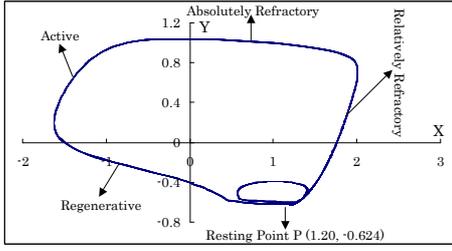


Fig. 6 Chaos trajectory

6. CHAOS BVP MODEL

The phenomenon of chaotic motion can be frequently seen in living body. For example when you stare at one point still without blinking, it appears that your eyeballs have stopped motion somewhat, but in fact the eyeballs are still making an infinitesimal movement that is called chaotic vibration. FitsHugh proposed BVP model in order to imitate the chaotic motion of nerves excitement in the potential plane [11]. The BVP equation can be deduced from the following differential equation.

$$\ddot{x} + c(x^2 - 1)\dot{x} + x = 0 (c > 0) \quad (8)$$

Here \dot{x} signifies the differential of x with respect to time, and we take a linear transformation as follow:

$$F(x) = \int_0^x f(u) du \quad (9)$$

Given the supposed (9) and the following transformed equation of (8):

$$\ddot{x} + f(x)\dot{x} + g(x) = 0 (c > 0) \quad (10)$$

We can obtain the following two differential equations related with two variants x and y .

$$\dot{x} = y - F(x) = y - \int_0^x c(u^2 - 1) du \quad (11)$$

$$\dot{y} = -g(x) = -x \quad (12)$$

The full BVP model form can be finally acquired by adding a stimulus item z and the BVP equation is acquired as follow:

$$\begin{aligned} \dot{x} &= c\left(x - \frac{x^3}{3} + y + z\right) \\ \dot{y} &= -\frac{x + by - a}{c} \end{aligned} \quad (13)$$

Here we will give biological definition about x and y arisen from BVP differential equation. The item x denotes the value of reversal sign of membrane voltage in cell and y signifies the refractory nature. The item z denotes the outer stimulus signal. Parameters a, b and c are confined as follow based on [12]:

$$1 - \frac{2b}{3} < a < 1, \quad 0 < b < 1, \quad b < c^2 \quad (14)$$

Fig.6 shows one example about the solution trajectory of BVP differential equation in x - y potential plane, and the nerve exciting process can also be obviously observed from this figure. In this chaotic locus, we adopt pulse signal as the stimulus. When proper stimulus signal shown

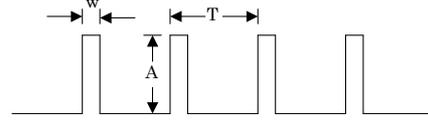


Fig. 7 The stimulus signal

TABLE 1

	A	T(ms)	W(ms)	type of response
(a)	· 0.8	100	3	2 stimulus : 1 response
(b)	· 0.91	100	3	5 stimulus : 4 responses
(c)	· 0.95	100	3	1 stimulus : 1 response
(d)	· 0.87	50	3	chaotic response

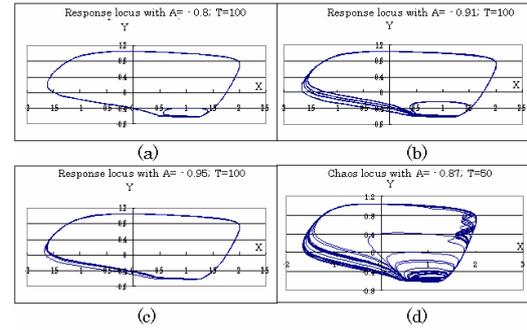


Fig. 8 The BVP response to stimulus

in Fig.7 comes, nerve excitement can happen. The respond process will start from Resting Point P , then pass through Regenerative part, Active part, Absolutely Refractory part, then Relatively Refractory part, and finally return back to Resting Point P again. In other words, the responsive trajectory has such characteristic that although the nerve cell is in a state of stillness originally, it will get excited once accepting a proper instant pulse signal and return to the stationary state in the end. The coordinate of resting point P is (1.20,-0.624) as one characteristic of BVP solution.

In order to apply chaos to the current intelligent system appropriately, the relationship between chaotic response and stimulus need to be examined. One proposed method called Rungekutta that has an relatively optimal performance in solving differential equation has been adopted to the BVP differential equation solution procedure. Now we merely let parameters A and T in BVP equation change with item W fixed to analyze the respond pattern. In the actual simulation by C program, if the amplitude A is strong enough and the T is long enough there will be a response once stimulus signal comes. On the contrary, if amplitude A is set weak enough or T short enough, there will not be any respond to stimulus no matter how frequent the stimulus comes. The respond pattern with different A and T is shown in Fig.8. The parameters of stimulus signal and various responsive types are shown in Table 1.

7. CATCHING-FISH EXPERIMENT

In order to examine whether the new system inserted with intelligent emotion imitation derived from chaos can

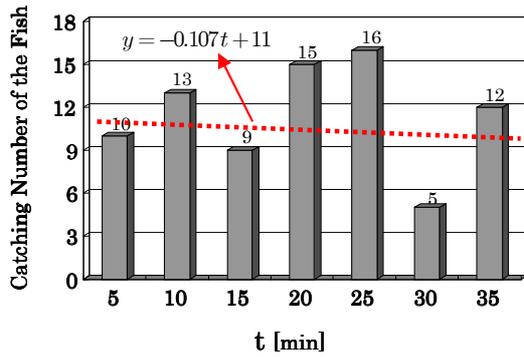


Fig. 9 Result of catching number

be more effective, we have tried the catching-fish experiment and finally showed that effective method can be created out against the animal escape strategy. The idea is to let the time when the fish threatened in pool corner wants to swim out coincide with the time when the net begins to perform chaotic motion in a probabilistic way. So outer situations to the animal to determine its next action can be thought to correspond with the stimulus signal to the BVP chaos model. In other words, we try to imitate the animal judging pattern (mind) in the chaotic way. By this way, it is considered that the time when the fish feels like getting out of the corner can match the time when chaotic motion is to be taken. Then the fish tends to be deceived that the scaring net is going further away and it can be caught by the net immediately once it swims out of the corner.

In order to check whether the new proposed catching fish system is more effective than the original one, we also kept catching 8 fishes in pool continuously under the same condition as the catching-fish experiment in Fig.3. We recorded the catching number of fishes every 5 minutes. The catching fish number kept decreasing in the former experiment shown in Fig.3. But after we embedded the chaotic motion to net movement this time and the catching number of fish does not go down as shown in Fig.9. Although the fish-catching number is somewhat uncertain with time, the average number is about 11 and the decreasing tendency has stopped. It had been thought the number would apparently decrease due to fish innate intelligence, but this experiment result in Fig.9 is satisfying because of the chaotic motion ensuring the number not to decrease. In other words, the chaotic motion have compensated the problem of fish escaping ability to escape from the catching-net.

As stated before, when the fish has finally gotten used to the net motion, it will be able to find out some escaping strategy to avoid the threatening net such as swimming within the pool corner where it is forbidden for the net to enter. So the catching number can become decreased as time flows. Now we tried another experiment to examine whether the chaos adoption can prevent the decrease of the Fish-Catching number and we used a different 8-fish group compared with the former experiment, with whose result shown in Fig.9. In this experiment we also released 8 fishes into the pool and keep

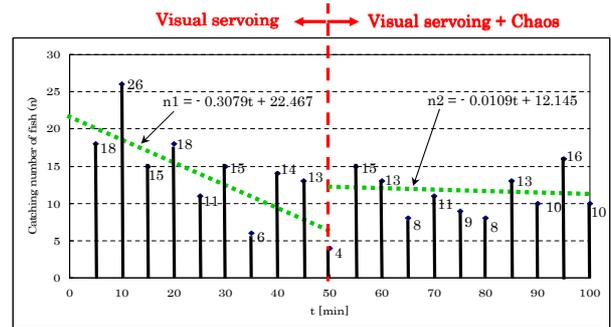


Fig. 10 Data analysis of the Fish-Catching number

tracking, catching and releasing operation continuously for 100 minutes, without chaos adoption during the first 50 minutes and with chaos used in the remaining 50 minutes. The result is shown in Fig.10, in which the horizontal axis represents time and vertical axis represents the Fish-Catching number in each 5 minute time span. To make the trend of catching-number obvious, we make separate analyses towards the former and latter 50-minute periods. From the two approximated curves denoted as n_1 and n_2 generated from Least-Squares method, we can see the Fish-catching number gradually decreased without chaotic motion used, but after 50-minute catching operation it can generally keep above the level of 11 fishes by adopting chaos. Altogether, the experiments shown in Fig.9 and Fig.10 have shown that the chaotic motion embedded to the catching-net is effective and can make the catching-fish operation go on smoothly even fishes gradually get used to the net motion pattern or find out some escaping strategies. From Fig.10, we can see the robot with chaotic motion used has effectively held down the fish learning ability in the longtime intelligence competition process between them because the FIQ has varied from -0.3079 to -0.0109 . Therefore the chaotic modification can overcome the fish intelligence and is useful for the contribution into the robotic intelligence realization.

8. CONCLUSION

We propose a new method so-called chaos embedded into the catching-net motion to cope with the the fish learning ability to escape from net. We suggest one more intelligent system than the traditional one in order to exceed the intelligence of the fish and the effectively of the system is testified in real experiments.

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