Neural-based control of a mobile robot: a test model for merging biological intelligence into mechanical system

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***Abstract*—The neuronal networks are considered as the origin of intelligence in organisms. In this paper, a new hybrid neuro-robot system merging the biological intelligence to the artificial intelligence was created. It was based on a neuronal controller bi-directionally connected to an actual mobile robot implementing a novel vehicle which was aimed at searching objects. The modified software architecture and home-made stimulation generator were employed to support a bi-directional exchange of information between the biological and the artificial part by means of simple binomial coding/decoding schemes. Eventually, the dissociated neuronal network could be successfully employed to control an artificial agent to find the objects. And the robot performed better and better along with the times of trials in one experiment because of the short-term plasticity. A new framework was provided to investigate the biological-artificial bi-directional interfaces for the development of innovative strategies for brain-machine interaction in these simplified model systems.**

I. Introduction

Although the artificial intelligence had a great progress for application in the actual life in past 50 years, algorithms on basis of the classical model of computation employed in the artificial intelligence system still get little solution about the problems of recognition, cognition, evolution, learning and memory. It seemed to be indicated that lack of a plastic development phase was one of the causes of these issues. But, this process has been found in the biological nervous system [1]–[4]. However, the brain network was difficult to present this plasticity phase in integration because of the extreme complexity of the brain structure. The dissociated neuronal network, which still maintained the primary characteristics of the biological neuronal network in different time and space scales [5]–[7], was served as a simplified model for further studies. This preparation not only could play as a groundwork for investigating the elementary rules of the neurosciences such as the mechanism of the information propagation, learning and memory, but also build a fundamental architecture for embodying the biological intelligence into the mechanical intelligence. Meanwhile, all the studies in this kind of system were expected to be applied to the final embodiment of the brain network and outer world agents.

In the past decades years, several neuro-robot hybrid systems have been developed [8]–[10]. A neuro-robot was a architecture system for embodiment of the biological and mechanical intelligence, in which the abilities of processing information in the biological system were employed to control an artificial body whose dynamics could be easily and completely modeled, in order to complete many specified tasks. These solutions provided the primary concepts of the neuro-robot. In previous studies, the stem cells [11], cortical neurons [8], [9], [12], hippocampal neurons [13], have been cultured to serve as the biological controller. Two kinds of architectures including master-slave [12] and integrated [8], [9], [13] structure have been designed to accomplish the neuro-robot system. However, there continued to be many problems existing in these systems. In some cases, a neuronal network did not constitute a central processing unit of the neuro-robot [14], [15]. In other cases, the plasticity phase of the neuronal network was not completely presented when the neuro-robot was employed to execute the specific tasks [12].

In order to improve these shortages, we built a closed-loop hybrid robot system by interfacing a differential mobile robot with a population of dissociated neurons, extracted from rat embryos and cultured on Micro Electrode Arrays (MEA). In this system, the dissociated neuronal network as an epistatic processor was designed to be able to directly control the robot based on a binomial decoding/coding algorithm to accomplish the task of searching objects. In our work, flexible modified software and home-made hardware architecture were developed to complete the closed-loop experiments. Meanwhile, A significant experimental improvement for robot control could be observed that robot system performance became better and better with the accumulation of the times of trials in one experiment. That may be a consequence of the plasticity change in the biological neuronal network. This neuro-robot system would be served as a simple model for reconstruction of the intelligence system.

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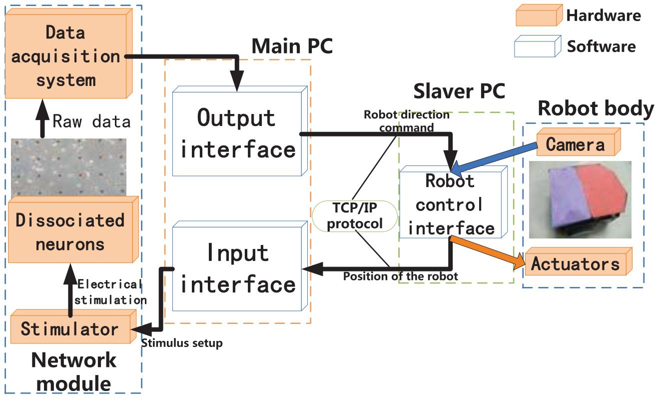

Fig. 1. Framework of the neuro-robot system. Three parts is included in this hybrid system:(i) network module, constituted by the data acquisition system(amplification, data acquisition card), the stimulator and the MEA coupled to living neurons; (ii) Main PC, employed to run the developed software tools; Output interface includes data preprocessing, recording, decoding and so on; Input interface includes coding (iii) Slave PC, hosting the robot control software to command the robot. The main PC communicates with the slaver PC by a mean of network port running the TCP/IP protocol.

II. NEURO-ROBOT ARCHITECTURE

The overall closed-loop system consisted of several modules including the software, hardware and wetware components (Fig. 1).

The wetware consisted of hippocampal neurons cultured on a standard 60-electrode MEA. Low density cultures of embryonic rat hippocampus were prepared as previously described [16] with modifications. Hippocampi were kept separate from embryonic day 18 (E18) rats and dissociated cells were plated on MEA chips at a density of 50-80 cells per mm2. MEA chips were coated with poly-L-lysine to facilitate cells adherence. Cultures of 14 to 20 days were used in the experiments. The hardware included: the MEA device where electrical signal was recorded by a MEA1060-Inv-BC amplification system (Multichannel Systems, MCS, Reutlingen, Germany), a home-made stimulating hardware, a directly linked workstation with a DAQ data acquisition card for conducting computationally expensive neuronal data analysis and a separate workstation running the robot control interface.

The home-made stimulator for dissociated neurons cultured on MEA was built around micro-controller which generated digital value for digital-to-analog converter (DAC) and sent necessary control signals to other circuits. The finished stimulator was able to generate an arbitrary defined biphasic voltage waveform with a time resolution of 3us and amplitude resolution of 12 bits for multi-electrodes at the same time. In order to complete the whole system, the stimulator was combined with the existing commercial recording system including MEA1060-Inv-BC amplification system and a data acquisition card (Multichannel Systems, MCS, Reutlingen, Germany). The whole finished hardware system was illustrated in Fig.2A. Meanwhile, various workstations in the architecture communicated via TCP/IP sockets (Fig. 1).

Two parts constituted the software of the whole system. One of the parts equipped in the separate workstation was compiled as a GUI interface to control the robot. The details will be described later. Another part modified from the toolbox written by Daniel Wagenaar (http://www.danielwagenaar.net/res/software/meabench/) ran on the directly linked workstation in a Linux operating system.This modified software, which reserved all the functions of the toolbox, was added some new functions in order to control all the parameters of the stimulation and perform the required data processing, such as communication with the robot control system, the implementation of the decoding/coding, spike detection, artifact filter and short- term plasticity schemes. Depending upon addition of the new functions, the signal of cultured neurons could be processed sufficiently to support the motion of the robot on the basis of a set of command lines and GUI utilities from the modified software.

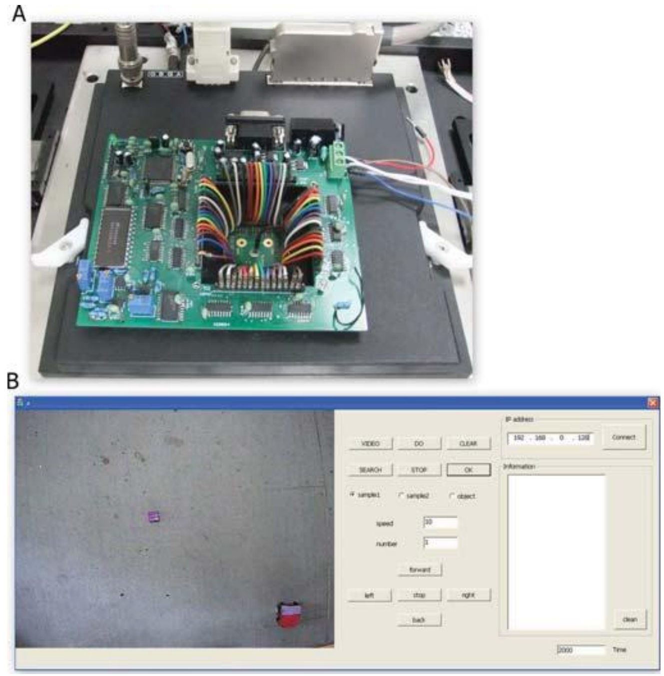

Fig. 2. Home-made stimulator and the robot control software. A. Implementation of the stimulator system including the pre-amplifier of the existing recording system.B. a graphical user interface (GUI) employed to control the robot. The monitor in the left side of the GUI is able to display the position of the robot in real time; these buttons in the middle of the panel is employed to manually control the robot; and the right side of the panel can connect with the main PC and display the information from/to the main PC.

III. ROBOT CONTROL SYSTEM

A differential mobile robot system used in our experiment consisted of a two-wheel differential mobile robot turning by the speed difference of the two wheels, a camera monitoring the information of the robot and objects, and a video acquisition card. Two different color papers were labeled on the robot to provide enough information for the video to confirm the position of the robot. A GUI interface written with MFC was employed to supply the basic control for the robot. As illustrated in Fig. 2B, this GUI was able to monitor the position of the robot and objects in real time, control the motion of the robot manually, and display the information of the communication between the robot and the cultured neurons. In our experiment, we designed the hybrid system to accomplish the searching-object task. Hence, this interface was ultimately used to transmit the relative position between the robot and the objects to the coding algorithm to decide the stimulation signal in real time, also receive the robot motion commands from the decoding algorithm at the same time.

IV. DECODING AND CODING STRATEGY

A. Decoding scheme

A kind of decoding scheme implemented in our hybrid system has been a frequency rate-based algorithm. For this scheme, all recorded signals were valuable. But a group of electrodes (i.e. a subpopulation of neurons) on the MEA was selected and defined as the output area for each stimulation before commanding the robot to move. The rest of electrodes was other area. The number of spikes occurring over all the electrodes in 1000ms after stimulation constituted the basis for calculating the motor signal for the corresponding external information. In the current architecture, a binomial relation was implemented between robot direction and motor signal: if the evoked firing rate per second calculated from the defined left (or right) output area exceeded the firing rate get from the other area with a threshold (80 per second),the robot would turn left (or right) immediately after the stimulation. If there was not any activities firing evoked by the stimulation in the neuronal network, the robot would receive a stop command. For the robot, the direction was therefore defined as:

$$\begin{cases} \frac{(\sum\limits_{i \in S_l} f_i - \sum\limits_{j \in S_o} f_j)}{t} \geq threshold & left, \\ \frac{(\sum\limits_{i \in S_r} f_i - \sum\limits_{j \in S_o} f_j)}{t} \geq threshold & right, \\ others & stop. \end{cases}$$

Where S_l, S_r and S_o denoted the totality of the electrodes in the corresponding output areas and other areas, respectively; f_i or f_j denoted the number of spikes in the ith or jth electrodes belonged to the corresponding areas. t was the time of sampling.

B. Coding scheme

The coding scheme was relatively simple contrast to the decoding scheme. Two groups of electrodes firstly were defined as input areas and assigned to the position of the robot on the left and right side of the objects. All electrodes which could evoke the neuronal network activities were confirmed to choose at least two electrodes, which the evoked firing activities by them were different from each other, to act as the input areas, and the areas where the neuronal activities evoked by the corresponding chose electrodes were intense, would be assigned to the output areas. As long as the relative position between the robot and the objects was confirmed and delivered to the coding algorithm, the coding algorithm would translate the received information to command the home-made stimulator to give a pair-pulse electrical stimulation with an amplitude 230 mv into the appropriate areas.

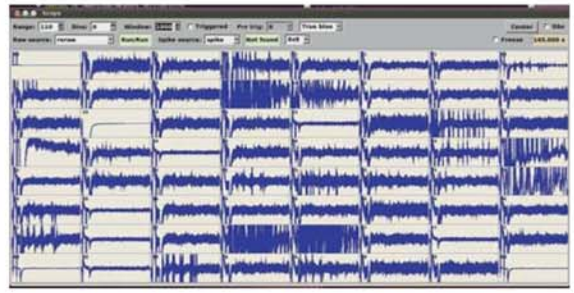

Fig. 3. A graphical user interface (GUI) for displaying the activities of the neurons. This GUI is run in the Linux operating system, and displays the raw electrodes data in a dissociated culture of 16 DIV. 1 second of activities evoked by the electrodes in the column 2 row 3 in total of 59 electrodes(electrode in row 5 column 1 is ground electrode) was acquired.

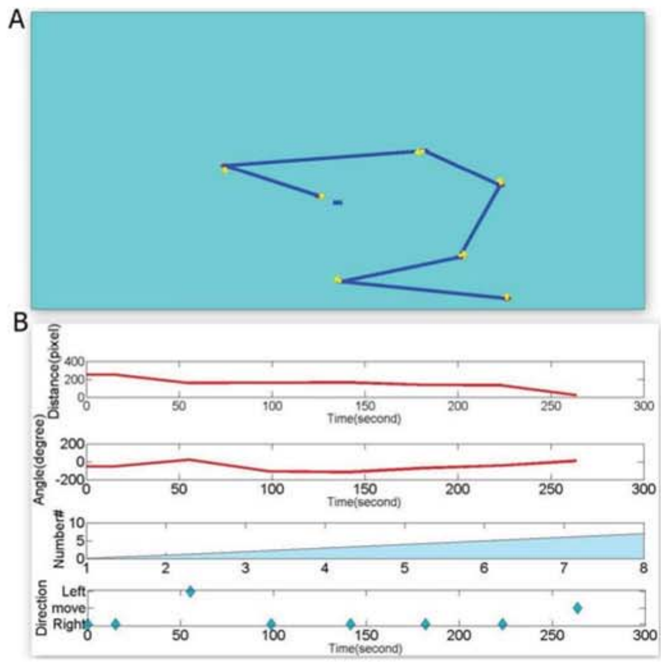

Fig. 4. An example of the neuro-robot with searching task. A. the trajectory of the robot in a successful searching task. The blue rectangle dot represents the location of the object, the yellow arrows represent the direction of the head of the robot, and the red circular dots represent the robots location where every time the neuronal network output the decision. B. the detailed data analysis of the searching task in A. from top to bottom, the first figure shows the distance between the object and the robot; the second figure shows the relative location between the object and the robot; the third figure shows the correct times of commands executed by the robot and the X label represents the number of total commands from beginning to now; the fourth figure shows the direction determined by the neuronal network.

V. RESULTS

A. Integration of the hardware and software

As the Fig. 3 illustrated, when the stimulation described in subsection Coding scheme was provided into the channel 23(channel 23 means the electrode located in column 2 and row 3 on an 8×8 electrodes array), the neurons growing around channels 12 16 17 24 25 35 36 38 41 42 45 47 51 52 55 57 58 73 74 75 84 85 and 87 could be excited and last 1 to 2 seconds. That indicated the stimulator was well able to act as a stimulation source to activate the neuronal network. Meanwhile, the modified software run in the Linux operating system was able to process the evoked neuronal activities well. We used a graphical user interface from the software toolbox to display the activities of the neuronal network in real time (Fig. 3), handled these activities in the background process of the operating system and recorded the activities into the disk at the same time.

B. Closed-loop robot control

The closed-loop robot control was implemented in our work. An example of the robot controlled by the neuronal network to find the objects was illustrated in Fig. 4A. In this example, the hybrid system could reach the objects within 300 seconds and performed 7 times turning which were all correctly executed by the robot during this time. At least 20 seconds interval time was necessary between two adjacent decisions (or two adjacent stimulation) from the neuronal network because of the existence of the refractory period of the neurons. Hence, the hybrid system spent a little more time on finding the objects. Even so, the robot would be more and more closed to the objects every time the robot turned (Fig. 4B). According to these indicators showed in Fig. 4, we demonstrated that a closed-loop system of which the controller unit was a dissociated neuronal network, could control a differential mobile robot to perform the specified task.

C. Plasticity change of the neuronal network in the neuro-robotic system

In order to sufficiently present the biological intelligence in this hybrid intelligent system, we would not stop the trial if the robot reaches the objects. However, the robot would be relocated to the start position and the trial would continue. Each trial would come to the end after a 15-minute operation. This step would be repeated for at least twice in consideration of the hypothesis that the neuronal network could dynamically modulate its activities to respond to the external information about a stable status along with the information was constantly delivered to the neuronal network. As an example of the plasticity change of the dissociated neuronal network in the neuro-robotic system, Fig. 5 showed that the performance of the robot get better and better along with the experimental process. In this example, time spent on finding the objects changed from 400 seconds, 320 seconds, to 260 seconds, and the correct turning ratio during this time had an obvious increase (right turning were from 71.4% to 100%, left turning were from 28.5% to 100%).

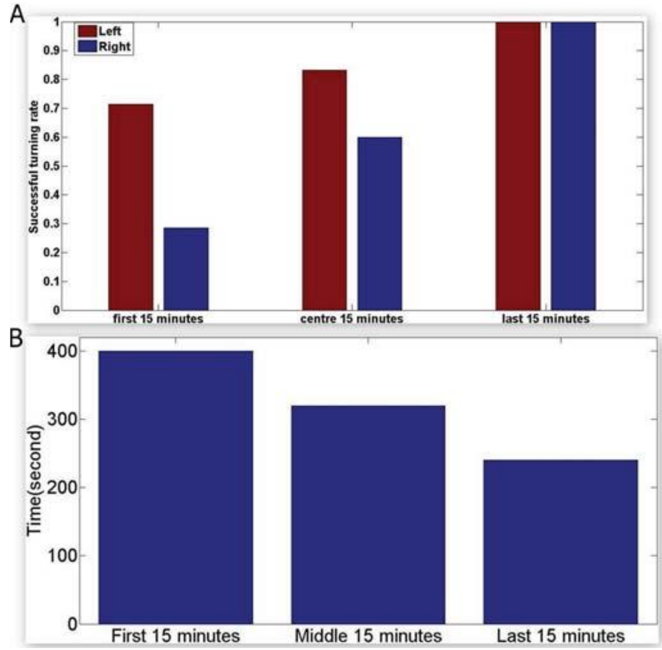

Fig. 5. Performance of the neuro-robot system.A. histogram of the correct turning percentage of the robot. The correct turning ratio of the two directions during three time phases are calculated, respectively. red bar is left turning, blue bar is right turning. B. histogram of the time which the robot spends on reaching the object during the three time phases. The datasets used in figure B are the same with A.

VI. Conclusion

In this paper, we successfully connected a dissociated neuronal network coming from the hippocampus of embryonic rats to a mobile robot system with a bi-directional way. In our examples, we were able to transform the spike frequency into the directions of the robot by employing a rate-based decoding strategy. Meanwhile transform the position information of the robot and objects into electrical stimulation for the neurons. In general, depending on these results, we demonstrated that an external agent could be successfully controlled by an in vitro network of biological neuron. Interestingly, the self-adaptive plasticity change of the dissociated neuronal network was observed and employed to improve the performance of the robot in our hybrid neuro-robot system.

Acknowledgment

The work has been supported by the Fundation of State Key Laboratory of Robotics (grant number is No.2013Z05) and the National Natural Science Foundation of China (grant number is No.51305438).

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