Visual Tracking and Servoing System for Experiment of Optogenetic Control of Brain Activity

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Abstract. To study the wireless optogenetic control of neural activity using fully implantable devices, we designed experiments that we make laser emit 980-nm light on the experiment mice brain where the upconversion nanoparticles which works as transducer to convert near-infrared energy to visible lights is implanted, observe the mice activity and record its trajectories. Hence, we propose and implement a automatic visual tracking and servoing system to aid and speed up the experiment. Usually, people drives PTZ for active surveillance tracking which aims to keep the object in the middle of the field of view. In this work, we utilize a PTZ to cast laser beam on the target object as the actuator (PTZ) and the sensor (camera) decoupled that they can be arbitrarily installed. And we also present the automatic parameters calibration method and mathematical modeling for this system to keep high accuracy.

Keywords: Visual tracking · Servoing · Calibration

1 Introduction

Optogenetics is a transformative tool for targeted control of neural circuits by using photo-sensitive proteins, and usually requires delivery of light with tethered fiber optics. In our another experiment, we present an all-optical alternative for wireless optogenetic control of neural activity using fully implantable devices based on upconversion technology which acts as a transducer to convert near-infrared (NIR) energy to visible lights for stimulating neurons expressing channelrhodopsin (ChR) proteins. As shown in Fig. 1, to achieve this target we have to cast the laser beam on the surgical wound where the device is implanted. While in order to observe the mice's reaction we have to allow the mice to freely move and record the mouse activity pattern which makes it impossible to

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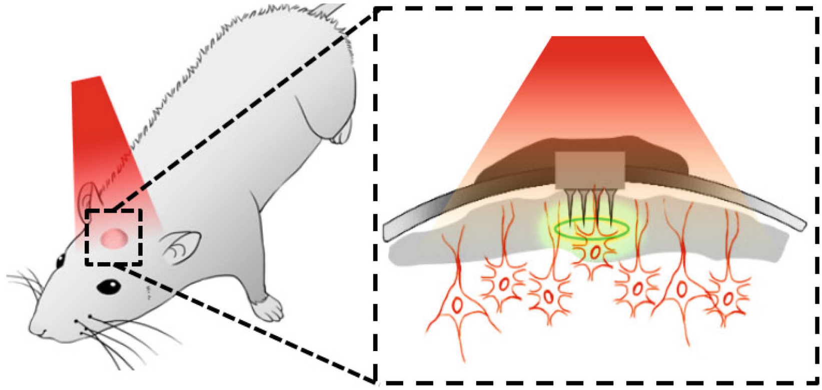
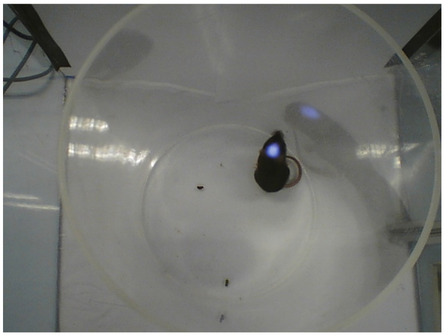


(a) Alternative optogenetic control experiment

(b) Mouse with device implanted at brain



(c) Experiment with one mouse

Fig. 1. Effect of tracking system. Illuminate the surgical wound of lab rat head by laser beam

manually do the job. Hence, we propose and implement the automatic tracking and servoing system which address both casting laser beam task and position recording task.

Visual tracking and servoing are challenging research topics which involves lots of field such as computer vision, control, automation and pattern recognition and so on. Lots of works have been done on these topics [2,13,14], and also some algorithms and applications have been proposed and presented like [3,20]. Nonetheless, even the state-of-art algorithm can not satisfy the requests of our designed system. Even the learning-based method [7,10] seems be the universal key to most of research fields. Since most approaches focus on the pure tracking, detection or servoing algorithm, our need is the user friendly and accurate system. In this paper, we present one tracking and servoing system which is third-person view instead of traditional camera-in-hand. What's more, we give out the accurate parameter calibration method and full system model to keep the accuracy.

The surveillance task is similar to ours. In order to cover wide area or get large field of view (FOV), it usually use the large FOV lens which introduce the image distortion or utilize the camera with PTZ [11]. Guha et al. [6] proposed a method to keep the target always in the middle of the field of view of the camera through adjusting the camera pose via PTZ. It uses mean-shift algorithm for visual tracking. Jain et al. [9] present a stationary-dynamic (or master-slave) camera assemblies to achieve wide-area surveillance and selective focus-of-attention. Their approach features the technique to calibrates all degrees-of-freedom (DOF) of both stationary and dynamic cameras, using a closed-form solution that is both efficient and accurate. There are many state-of-the-art algorithms or approaches available for surveillance systems indeed, but as mentioned before, our system has negligible difference with them that the sensor and actuator are soft or arbitrarily linked which involves the extra parameters. And due to the mice's intense reaction our system is required to have high precision and dynamic performance.

In this work, based on the design request we integrate the visual tracking, servoing and automatic calibration in the proposed system. The change of structure makes our system different from the camera-PTZ control case which most are self-adjusting and involved extra calibration problem. Our proposed tracking and servoing system successfully solves above difficulties via system structure modeling and automatic calibration approach. Our contributions in this work are listed as follow:

- We propose and implement a automatic tracking and servoing system which has been successfully applied on the real biological experiments.
- We present full parameters mathematical model which is able to give a close-form solution. It greatly reduces the complexity of our tracking system since we don't have to utilize complicated control systems.
- Based on the model we introduce the automatic parameter calibration strategy and it is the foundation of arbitrary deployment.

The rest of the paper is organized as follows. Section 2 gives the overview of the tracking and servoing system. The visual object detection, model and parameter calibration are given in Sects. 3 and 4, respectively. Section 5 contains the experiments. Finally, Sect. 6 summarizes the paper.

2 System Overview

Figure 2 gives the overview of our system deployment. The tracking and servoing system mainly includes the camera, laser collimator with Pan-Tilt, holders, embedded controller board and PC. In Fig. 2, ④ is the IoT control board called ATOM which is small but powerful core, comprised of DUAL high performance processors (STM32 MCU and Linux-in CPU). It works as the lower level controller of the Pan-Tilt and makes it act according to the command from the PC [5,15–19]. The camera and Pan-Tilt are arbitrarily mounted whose only requirement is that their workspace or FOV can cover the target plane ③. Our system features friendly-usage, automatic calibration, low coupling of modules

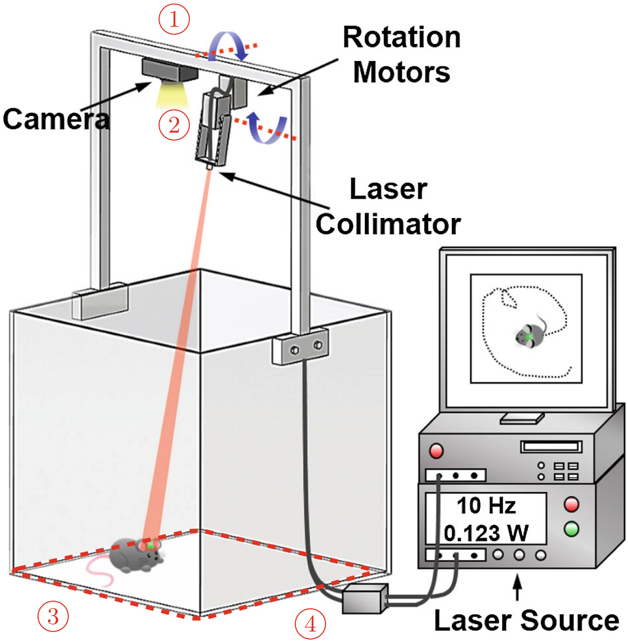


Fig. 2. Framework overview. ① Arbitrarily mounted camera ② Laser with Pan-Tilt ③ Target plane ④ IoT ATOM board

and extensibility. It can be taken as a tracking and servoing framework since its decoupled modules are easily replaced by other algorithms or approaches.

The workflow of our system is shown in Fig. 3 which contains two phases, calibration phase and execution phase. During the calibration phase, the primary work is to calibrate the system parameters: Pan-Tilt offsets. As shown in Fig. 2, it's not practical to directly accurately measure the system parameters. Hence, we propose the automatic calibration procedure to get these parameters by driving the Pan-Tilt to zigzag scan the plane. With the structure model and derived calibration formulas we know the minimum number of sample data is 7. The execution phase is a common detection-servo loop which keeps the laser spot on the brain of mice. We apply the visual methods on the image captured by the camera to locate the mice brain and laser spot and then calculate the commands α, β of the Pan-Tilt with the calibrated parameters. The dashed border block in Fig. 3 represents one optional module that offers feedback to the Pan-Tilt controller. We don't implement this module in our system but it won't be hard to implement and integrate.

3 Visual Detection

Object detection and tracking are very challenging problems that have been drawing lots of interests for couples of yeas. And many powerful algorithms or

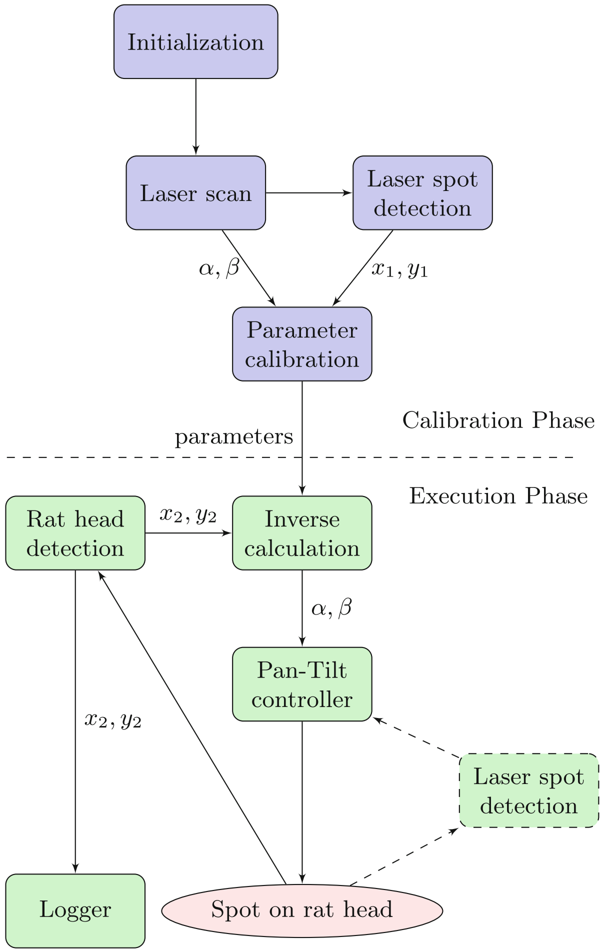


Fig. 3. System work flow. x_1, y_1 are laser spot position, x_2, y_2 are mice brain position. α, β are the pan and tilt angle

approaches such as Kalman filter-based algorithms [4] and CONDENSATION algorithm [8] have been proposed [21,22]. Especially, with the popular of neural network, the new learning-base approaches can handle much more complex environment and give out more accurate output information.

Considering the static and controllable environment of our case, the tracking problem of our system can be simplified and replaced by detection problem. The state-of-art learning-based detection approaches are very sophisticated and able to output accurate position but at the cost of speed which is an old truism. In this work, the laser stimulation will lead to the strenuous activity of mice and, accordingly, we prefer the high processing speed by applying color and geometry based detection methods.

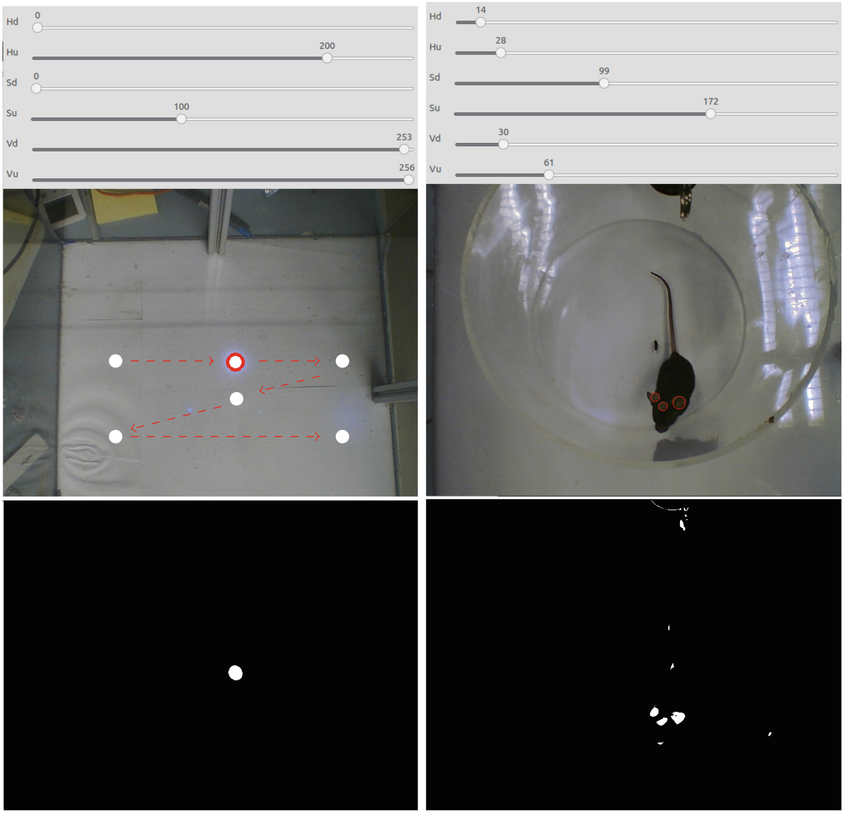


Fig. 4. Laser spot (left) and surgical wound of mouse brain (right) detection. Left: red circle marks the laser spot, red dashed arrow lines mark the scan path (Color figure online)

Visual detection approach serves in both parameter calibration phase and execution phase in this work. For parameter calibration, we detect the laser spot on the target plane and the location serves as the input of calibration algorithm with the control command. And for execution phase, we detect the surgical wound on the brain of the mouse which the is target position laser spot should be. As shown in Fig. 4, the laser spot has pure color, high light intensity and typical blob shape. In consideration of these characteristic of the detection target, we utilize the blob detection under HSV color space to locate the target position. We use the blob detector from OpenCV [1] which provides various and out-of-the-box algorithm implementations. As shown in Fig. 4, we first convert the image to HSV color space and get the threshold which the key parameter for blob detector. We manually set the filter parameters of the detector for different target and take the average of the blobs location as the rat head location for the surgical wound case.

4 Model and Parameter Calibration

The detailed structure of Pan-Tilt is shown in Figs. 5 and 2 shows the big picture of the deployment. We have two servo marked as ① and ② respectively and one laser emitter. First, we define the world frame as $O_0x_0y_0z_0$ which is the initial pose of first servo frame $O_1x_1y_1z_1$ and second servo frame as $O_2x_2y_2z_2$. z_0 and z_1 are the rotation axis of first servo and y_2 are the rotation axis of second servo. y_1 is parallel to y_2 and then we have only two offsets a_1, a_2 along x, z axis. We also assume that z_2 is the laser direction and the laser emitter has two offsets a_3, a_4 along x, y axis with respect to second servo. Let α, β represent the rotation angle of two servos. Finally, we have four parameters a_1, a_2, a_3, a_4.

Fig. 5. Actuator overview. ① First servo ② Second servo ③ Laser emitter ④ Rotation axis of first servo ⑤ Rotation axis of second servo

Let $\boldsymbol{a} = \begin{bmatrix} a_1 \ a_2 \ a_3 \ a_4 \end{bmatrix}^T$. With the help of our previous work [12] it's easy to know the laser direction $\boldsymbol{v}$

$$\boldsymbol{v} = \begin{bmatrix} \cos\alpha\sin\beta \\ \sin\alpha\cos\beta \\ -\sin\alpha \end{bmatrix}$$

and laser emitter position $\boldsymbol{E}$:

$$\begin{aligned}\boldsymbol{E} &= \begin{bmatrix} a_1 + a_3 \sin\alpha + a_4 \cos\alpha \sin\beta \\ a_3 \cos\alpha + a_4 \sin\alpha \cos\beta \\ a_2 + a_4 \cos\beta \end{bmatrix} \\ &= \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha & \cos\alpha \sin\beta \\ \sin\alpha & 0 & \cos\alpha & \sin\alpha \sin\beta \\ 0 & 1 & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} \\ &= C\boldsymbol{a}\end{aligned}$$

Then any point P_i on the target plane can be present as:

$$P_i = C_i\boldsymbol{a} + r_i\boldsymbol{v_i} = x\boldsymbol{P_0P_x} + y\boldsymbol{P_0P_y} + P_0 \tag{1}$$

where P_0, P_x, P_y are three selected base points on the target plane. Let's reorganize the Eq. 1 and get:

$$\begin{aligned}&[x_i(C_1 - C_0) + y_i(C_2 - C_0) - (C_i - C_0)]\boldsymbol{a} \\ &\qquad + (1 - x_i - y_i)r_0\boldsymbol{v_0} + x_ir_1\boldsymbol{v_1} + y_ir_2\boldsymbol{v_2} - r_i\boldsymbol{v_i} = 0\end{aligned} \tag{2}$$

By driving the laser zigzag scan the target plane we can collect enough sample data P_i for calibration. Equation 2 can be represented as the homogeneous system of liner equations in shape of $B\boldsymbol{x} = 0$ and $\boldsymbol{x} = \begin{bmatrix} a_1 \; a_2 \; a_3 \; a_4 \; r_1 \; \ldots \; r_n \end{bmatrix}^T$. With the input $\begin{bmatrix} \alpha_i \; \beta_i \; x_i \; y_i \end{bmatrix}$ $(i >= 7)$ we can solve it by SVD to get the parameters $\begin{bmatrix} a_1 \; a_3 \; a_4 \; r_0 \; r_1 \; r_2 \end{bmatrix}$ (a_2 cannot be solved but doesn't affect the system).

For the execution phase we need the inverse kinematic to calculate the command $[\alpha, \beta]$ as given the $[x, y]$. With the simple constraint that $\boldsymbol{EP_i}$ should be parallel to the laser direction $\boldsymbol{v}$ we can get:

$$\begin{aligned}0 &= \boldsymbol{EP_i} \times \boldsymbol{v} \\ &= (\boldsymbol{EP_0} + \boldsymbol{P_0P_i}) \times \boldsymbol{v} \\ &= (C_0\boldsymbol{a} + r_0\boldsymbol{v_0} + x_i\boldsymbol{P_0P_2} + y_i\boldsymbol{P_0P_3} - C_i\boldsymbol{a}) \times \boldsymbol{v}\end{aligned} \tag{3}$$

By solving the Eq. 3 we can get exact solutions $[\alpha_i, \beta_i]$ for a detected point P_i.

5 Experiments

Our proposed system has been successfully applied to our optogenetic control experiments which got expected outcome. The system largely reduces the experiment time, increases the level of automation and shows high performance during the experiments. Figure 6 shows our field test and the laser beam sticks to the surgical wound on the mouse brain. Although laser spot is not perfectly coincident with the camera detected position, the laser spot is a dot with certain size instead of ideal point which compensate the position error. Considering the limited resolution of Pan-Tilt, the system has met our requirement. In the third figure of Fig. 6, we see the mouse stands up which doesn't satisfy our plane object assumption and this is the main point of our future work to extend our system to 3D space.

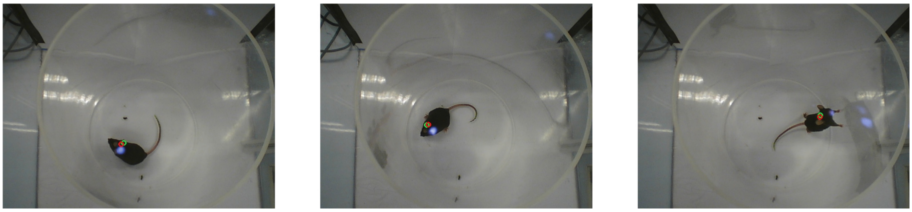


Fig. 6. Field test. Circles are the position detected by camera and purple spot is laser spot (Color figure online)

6 Conclusion

In this paper, we present a visual tracking and servo system which features low coupling, easy deployment and automatic parameter calibration. The proposed system has been successfully applied to our biological experiments and speeded up the process of experiments. With the help of automatic calibration approach, the camera and Pan-Tilt can be arbitrarily set up that traditional approaches don't have this capability. Moreover, as mentioned above our model is based on the 2D plane and objects usually are 3D or move in 3D space (last one in Fig. 6). Hence, Extending the system to 3D space is one of our future work. And we also will integrate better visual tracking and detection methods in the future.

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