Method Article

An open source motorized swivel for in vivo neural and behavioral recordings

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ABSTRACT

In this work we propose an open source, cost-effective motorized swivel for behavioral and neural recordings in small rodents, offering a flexible solution for managing cable twisting and tangling in a variety of experimental settings with minimal human supervision.

- The device operates independently of the data acquisition system, and it can be controlled through any popular platform such as Arduino or Raspberry Pi.
- All mechanical parts are 3D-printed, allowing to customize the design to fit specific experimental needs, and electromechanical components can be sourced from all major distributors, keeping the cost for the entire system under $500.
- The proposed commutator is compatible with commercial or custom data acquisition systems supporting up to 10 data lines (2 for LVDS signals) and 2 power lines.

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Specifications table

| Hardware name: | Motorized swivel |
|----------------|------------------|
| Subject area:  | Neuroscience (in vivo behavioral and neural recordings). |
| Hardware type: | Lab cable interface for neural and behavioral recordings. |
| Open source license: | GNU GPL |
| Cost of hardware: | $500 |
| Source file repository: | https://osf.io/wq897/ https://3dprint.nih.gov/discover/3dpx-013630 |

### Hardware in context

There are several options for motorized commutators available on the market today, however their proprietary design makes their use limited to specific recording hardware, and their cost can be a critical limiting factor in the experiment design. A custom commutator based on torque sensing through a Hall sensor for chronic recordings in zebra finch was developed in [6,7]. Based on similar working principles, the proposed system offers a more contained and portable solution, ideal for small rodents recordings, and it includes two LVDS lines used in most miniature imaging systems. The proposed commutator system offers a flexible interface adaptable to a variety of neural and behavioral recording systems, with an overall contained cost.

### Hardware description

Here we propose a cost-effective, custom motorized swivel system, particularly helpful for in vivo recordings with small rodents. Unlike commercially available motorized commutators, it offers both the flexibility of being paired with a variety of recording systems (any apparatus using up to 12 connections), and the manufacturability, scalability and cost-effectiveness which results from the use of 3-D printed parts, off-the-shelf components, and open source control software. The main advantages of the proposed system are:

- Cost-effectiveness can scale up experimental throughput while reducing the required human supervision.
- The open-source design makes it easy to modify the design for custom needs, such as the use of a specific connector, or pairing the commutator with an optical fiber.
- The device can be easily manufactured with the equipment available in most laboratories and off-the-shelf components available online.

An overview of the system in a practical behavioral context is shown in Fig. 1.

### Materials and methods

The proposed system comprises custom 3-D printed parts (listed in Table 1), off-the-shelf discrete mechanical and electrical components (summarized in Tables 2 and 3, respectively), and custom

| Component            | Description                                      | File name       |
|----------------------|--------------------------------------------------|-----------------|
| 1. Stator            | Stator                                           | 01 stator.stl   |
| 2. Rotor             | Rotor                                            | 02 rotor.stl    |
| 3. Top lid           | Stator lid, hosting stator PCB                   | 03 top lid.stl  |
| 4. Bottom lid        | Rotor lid, hosting rotor PCB                     | 04 bottom lid.stl |
| 5. Motor frame       | Frame for securing motor and slipring            | 05 frame.stl    |
| 6. Pulley 1          | Motor shaft pulley                               | 06 pulley1.stl  |
| 7. Pulley 2          | Slipring pulley                                  | 07 pulley2.stl  |
| 8. Rotor shaft holder| Contains ball bearings and shaft driven by cable | 08 rotor shaft.stl |
| 9. Magnet holder     | Stator                                           | 09 magnet holder.stl |
Fig. 1. Overview of the system. (A) Diagram showing a practical application of the proposed system paired with in vivo calcium imaging with miniScope [8,2]. (B) A picture of the assembled commutator.

Table 2  
List of discrete off-the-shelf mechanical components. For the complete description and part numbers see [4].

| Component | Function                          | Qty | Ext. price  |
|-----------|-----------------------------------|-----|-------------|
| 1. Ceramic capacitor .1μF          | Motor noise suppression capacitors| 3   | 1.44 USD    |
| 2. 6 Position JST SH-type cable    | Motor/encoder cable               | 1   | 1.35 USD    |
| 3. 9 Position JST SH-type cable    | Slip ring to PCB connections      | 2   | 5.38 USD    |
| 4. Rod magnet                       | Magnet for detecting cable rotation| 1  | 0.37 USD    |
| 5. Face-mount crossed-roller bearing| Stator to rotor ball bearing      | 1   | 148.56 USD  |
| 6. 2 mm stainless steel rod        | Rod for cable rotation            | 1   | 9.64 USD    |
| 7. Copper alligator clip           | For securing cable to rod         | 1   | 0.70 USD    |
| 8. Ball Bearings for 2 mm shaft    | Cable rod ball bearings           | 2   | 14.06 USD   |
| 9. Hex nuts M1.6 × 0.35 mm         | Securing rotor shaft holder to bottom lid | 3   | 9.61 USD    |
| 10. Hex nuts M2.6 × 0.45 mm        | Securing slip ring to frame       | 3   | 1.57 USD    |
| 11. M3 screws 0.5 mm × 10mm         | Securing ball bearing to stator   | 10  | 4.97 USD    |
| 12. M1.6 screws 0.35 mm × 3 mm      | Securing motor to frame           | 10  | 13.28 USD   |
| 13. M1.6 screws x 0.35 mm × 5 mm    | Securing frame to stator          | 2   | 12.69 USD   |
| 14. M2.6 screws 0.45 mm × 5 mm      | Securing slip ring to frame       | 3   | 8.35 USD    |
| 15. Hex nuts M3 coarse pitch        | Securing ball bearing to stator   | 6   | 5.55 USD    |
| 16. M1.6 Phillips screws            | Securing top/bottom lids to stator/ rotor, rotor shaft holder to bottom lid | 13  | 9.41 USD    |
| 17. 18–8 Set Screw 0–80 × 1/16”    | Securing rod ball bearing to rotor shaft holder | 2   | 8.78 USD    |
| 18. 75:1 Micro Metal Gearmotor     | DC motor for driving slip ring    | 1   | 18.95 USD   |
| 19. Magnetic encoder                | Encoding motor shaft angular position| 1  | 7.95 USD    |
| 20. Timing belt, 1 mm pitch         | Timing belt between motor and slip ring pulleys | 1  | 1.30 USD    |
| 21. Senring slip ring M012A-18      | Slip ring                        | 1   | 17.50 USD   |

Tot. 301.41 USD  

Note: prices for smaller hardware components, such as screws and nuts, are adjusted according to distributor’s minimum quantities.
printed circuit boards (PCBs) for rotor and stator. A complete list of components, PCB gerber files and bill of materials (BoM) can be found in [4].

All 3-D printed parts are available at the NIH 3D Print Exchange Library [3], and can be printed using an in house 3-D printer such as Form 2 (Formlabs, Somerville MA), or using any online 3-D printing service such as 3D Hubs (standard ABS, 80% infill, 100 µm). An overview of all the components and the assembled prototype is shown in Fig. 2.

The electro-mechanical components required for the assembly are all available for purchase online.

**Build instructions**

Assembling the motorized commutator is a two-step process: first the electronic components need to be soldered onto the PCBs, then all the electro-mechanical components need to be assembled together. A step-by-step video illustrating the motorized swivel assembly is available at the following link: https://www.youtube.com/watch?v=Jbc3p22F6 94 [5].

The PCB assembly requires a minimal number of surface mount components, which can be easily installed on the PCBs using a soldering iron, hot plate, hot air gun, or reflow oven. Since soldering irons are widely accessible to most labs, this technique will be considered below. Working under a microscope is helpful when dealing with smaller components. All PCB artwork files, bill of materials, stencils and component positioning files can be found at [4].

1. If using a stencil: secure PCB to workbench with lab tape and position stencil on top, aligning holes to solder mask openings. Secure stencil to workbench with lab tape and, with the help of a spatula, apply solder paste to fill evenly all stencil openings. Without stencil: use a needle or small tip to apply solder paste to all pads.
2. Following the component positioning reference (Fig. 3, [4]), place all components in their respective position, ensuring good contact with solder paste.
3. Keeping component in place with a tweezer, melt the solder paste to the pads with the soldering iron, one component at a time. When done, repeat steps 1–3 for the other layer.
4. Clean solder paste residue with a cleaning agent such as isopropyl alcohol and a small brush.
5. Apply a layer of non-conductive epoxy between connectors and PCB, taking care not to spill over on the contacts, to strengthen their resistance to mechanical stress.

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Table 3
List of discrete off-the-shelf electrical components to be mounted on rotor and stator.

| Ref. Des. | Component | Qty | Ext. price |
|-----------|-----------|-----|------------|
| **Stator PCB** | | | |
| 1. C5 | CAP CER 0.47UF 25 V X5R 0603 | 1 | 0.18 USD |
| 2. C1, C4 | CAP TANT 10UF 10% 16 V 1206 | 2 | 0.86 USD |
| 3. U1 | CONN HEADER SMD R/A 6POS 1MM | 1 | 0.83 USD |
| 4. JP1, JP2 | CONN HEADER SMD R/A 9POS 1MM | 2 | 1.96 USD |
| 5. C2, C3 | CAP CER 0.1UF 16 V 10% X7R 0402 | 2 | 0.20 USD |
| 6. R1 | RES 0.0 OHM 1/10 W JUMP 0603 SMD | 1 | 0.10 USD |
| 7. U16 | OMNETICS PZN-12-AA | 1 | 29.00 USD |
| 8. Q1 | MOSFET P-CHAN 24 V SOT23 | 1 | 0.43 USD |
| 9. IC1 | TB6612FNG | 1 | 1.95 USD |
| 10. U14 | Connector Receptacle µHDMI SMD | 1 | 2.66 USD |
| **Rotor PCB** | | | |
| 1. LED1 | LED GREEN CLEAR THIN 0805 SMD | 1 | 0.30 USD |
| 2. JP3, JP4 | CONN HEADER SMD R/A 9POS 1MM | 2 | 1.96 USD |
| 3. C6 | CAP CER 0.1UF 16 V 10% X7R 0402 | 1 | 0.10 USD |
| 4. U3 | OMNETICS PZN-12-AA | 1 | 29.00 USD |
| 5. U2 | ROTARY ENCODER MAGNETIC | 1 | 5.38 USD |
| 6. R4 | RES 1 K OHM 1/10 W 1% 0603 SMD | 1 | 0.10 USD |
| Tot. | | | 75.01 USD |
Fig. 2. Motorized swivel assembly. (A) Overview of the 3D-printed parts and electromechanical components; numbering corresponds to line items of Table 1 (in red) and Table 2 (in blue), respectively. (B) Exploded view of the stator assembly. (C) Exploded view of the rotor assembly. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The steps for assembling the mechanical parts are outlined below:

1. Using the appropriate screws and nuts as directed in Table 2, secure motor and slip ring to frame (Video 06:59), then press fit their respective pulleys and install the timing belt (Video 07:22). Fully tighten motor screws only after timing belt is in place, making sure it is taut around the pulleys.
2. Solder the magnetic encoder board (item #19 in Table 2) to the back of the motor (Video 00:44). First center the motor shaft to the PCB hole, keeping it in place with a soldering clamp, then apply solder to the motor pins.
3. Set up the slip ring connections (Video 01:18): although not necessary, it is recommended to use pre-crimped JST cables (line item #3 in Table 2) rather than crimping directly the slip ring wires. Cut the JST wires to have 30 mm leads on each end, and the slip ring wires to have 50 mm on each end. With a wire stripper expose the conductor from all wire tips and, following the diagram in Fig. 4A, route all wires from the slip ring to the four 9-pin JST connectors. Use shrink tube to cover exposed solder and avoid short circuits between wires.
4. Secure roller bearing to stator and rotor (Video 05:46).
5. Mount the two ball bearings at the two ends of the shaft holder, securing them in place with the set screws (Video 09:17).
6. Insert rod through ball bearings, and use epoxy to glue magnet to the end of the rod (Video 09:24).
7. Slide shaft holder through rotor hole from the inside, and secure with the 3 screws and nuts (Video 09:31).
8. Mount stator and rotor PCB to top and bottom lids (Video 10:20).
9. Pass the two rotor JST connectors through the hole in the roller bearing (Video 08:06), and secure the frame to the stator with the two designated screws (Video 08:50).
10. Connect the slip ring to stator and rotor PCBs, and the motor to the stator PCB (Video 11:07).
11. Screw top and bottom lid to stator and rotor, respectively (Video 11:55).
12. Using epoxy, attach alligator clip for holding the cable to the end of the rod (Video 09:52).

Troubleshooting:

- **Issue: electrical connections not working.** Possible reason 1: some of the connector were not properly soldered, resolder and test connectors before applying epoxy. Possible reason 2: JST connectors not properly soldered: check the integrity of all traces at the JST connector from one side to the other of the swivel, resoldering faulty connections.
- **Issue: motor not running.** Possible reason 1: malfunctioning of the Hall sensor reader. Check the output from the Hall sensor reader, and make sure that the green LED in the rotor PCB is on when the board is powered, indicating proper distance of the magnet to the sensor. Possible reason 2:
mechanical friction is stalling the motor. If controlling the motor with a 50% PWM duty cycle in either direction does not engage the motor, check for possible mechanical parts obstructing the motion, or excessive tension on the belt.

- **Issue: motor running, but rotor not moving.** Possible reason 1: belt slipped from the pulleys, likely due to misalignment or insufficient distance between the pulleys. This can be caused by warping of the motor frame if the material is not strong enough, in which case tape or an elastic band can be looped around motor and slipping to adjust pulley distance and ensure that the belt is properly engaged. Possible reason 2: belt does not have traction on pulleys, likely due to low teeth profile. This can happen if the 3-D printer tolerance is not precise enough, one possible solution is to reprint the pulleys with higher tolerance or reprint them from a different source.

- **Issue: rod slips easily out of ball bearings.** With a needle apply a small amount of epoxy between rod and lower ball bearing, making sure when drying epoxy does not spill into the ball bearing.

- **Issue: screws do not fit holes.** In many cases, due to 3-D printing tolerances, screw hole sizes will need to be increased with a hand drill and appropriate bit.

- **Issue: when using with calcium imaging, data is noisy.** Possible reason: Differential signal is picking up noise in the swivel. Make sure to use GPIO3 and GPIO4 lines for the differential signal, and twist-pair the respective wires on the slipring.

### Operation instructions

The motorized commutator is controlled independently from the recording apparatus, with an Arduino Uno (ATmega328P) microcontroller [1] connected through a micro HDMI type D cable (Fig. 5). With a minimal number of parameters, the control algorithm does not require tuning to adapt to any particular application, thus minimizing the required human supervision for cable management during experiments. Sample code for implementing the control algorithm on Arduino Uno is provided in Appendix A. The connections for interfacing data acquisition hardware and recording apparatus are outlined in the wiring diagram in Fig. 6.
Discussion and future work

The proposed motorized swivel can be integrated in a variety of experimental settings, most relevantly in rodent neural recordings such as electrophysiology or calcium imaging. We tested the motorized commutator in an open field recording of a freely behaving mouse wearing a miniature epifluorescence microscope (miniScope [8]) for calcium imaging. Results are shown in Supplementary video 1.

In some cases (as for electrophysiological recordings) more than 12 channels could be required. With minimal modifications to the overall design (i.e. modifying only the motor frame to accommodate the new slipring, and the rotor pulley inner diameter on the slipring side) it is possible to increase the number of channels. For example, with the M250-56 slipring, one can use up to 56 channels (the flange will need be trimmed to fit the motor). The additional channels can be soldered on both sides to a custom connector for interfacing with the specific recording hardware. As an extension of the system to simultaneous neural recording and stimulation through optogenetics, as well as coupling with other fiber-optics imaging systems, one possible development could be to integrate a fiber-optics channel in the center of the swivel.

The use of a flexible control platform like Arduino allows to customize the control algorithm for satisfying specific experimental requirements. Although in most cases a proportional controller
is enough to guarantee the basic automated commutator functionality, more sophisticated control algorithms can be implemented, and different platforms than Arduino can be used to pair the commutator with an existing data acquisition system.

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**Declaration of Competing Interest**

The Authors confirm that there are no conflicts of interest.

**Supplementary materials**

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.mex.2020.101167.

**Appendix A**

Sample code for controlling the motorized commutator through Arduino Uno (ATmega328P) microcontroller.

```c
// Motorized commutator control

#define PWENC 2 // A85030 pwm readout, pin 2 on Arduino Uno (interrupt 0)
#define PWM A 3 // Motor driver PWM
#define AIN1 7 // Motor direction input 1
#define AIN2 4 // Motor direction input 2
#define STBY 8 // Motor driver standby (1 for normal operation)

const int MIN_CH = 10; // Minimum reference angle change to move
const int MOTOR_MAX_SPEED = 90; // Maximum motor speed
const int MOTOR_K = 1; // Speed proportional factor
volatile int ref_angle0;
volatile int t0;
int ref_angle_cal = 0;
int ref_angle = 0;
bool init_done = 0;

void setup() { 
  pinMode(PWENC, INPUT);
  pinMode(PWMA, OUTPUT);
  pinMode(AIN1, OUTPUT);
  pinMode(AIN2, OUTPUT);
  pinMode(STBY, OUTPUT);
  attachInterrupt(0, rising_edge, RISING); // Interrupt 0 attached to pin 2
  init_done = 0;
}
```
```c
void loop() {
    int c_speed = 0;
    int dir = 0;
    ref_angle = ref_angle0 - ref_angle_cal;

    // Calibration
    if (init_done == 0) {
        delay(100);
        ref_angle_cal = ref_angle0;
        init_done = 1;
    }

    c_speed = MOTOR_K * abs(ref_angle); // Set motor speed
    dir = get_dir(ref_angle); // Set motor direction

    if (abs(ref_angle) > MIN_CH) {
        if (c_speed > MOTOR_MAX_SPEED) {
            c_speed = MOTOR_MAX_SPEED;
        }
        motor_go(dir, c_speed);
    } else {
        c_speed = 0;
        motor_stop();
    }

    init_done = 1;
}

void rising_edge() {
    attachInterrupt(0, falling_edge, FALLING);
    t0 = micros();
}

void falling_edge() {
    attachInterrupt(0, rising_edge, RISING);
    ref_angle0 = micros() - t0;
}
```
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