Open source affordable rotary stage for 2D navigation in mice for Neuroscience and behaviour experiments

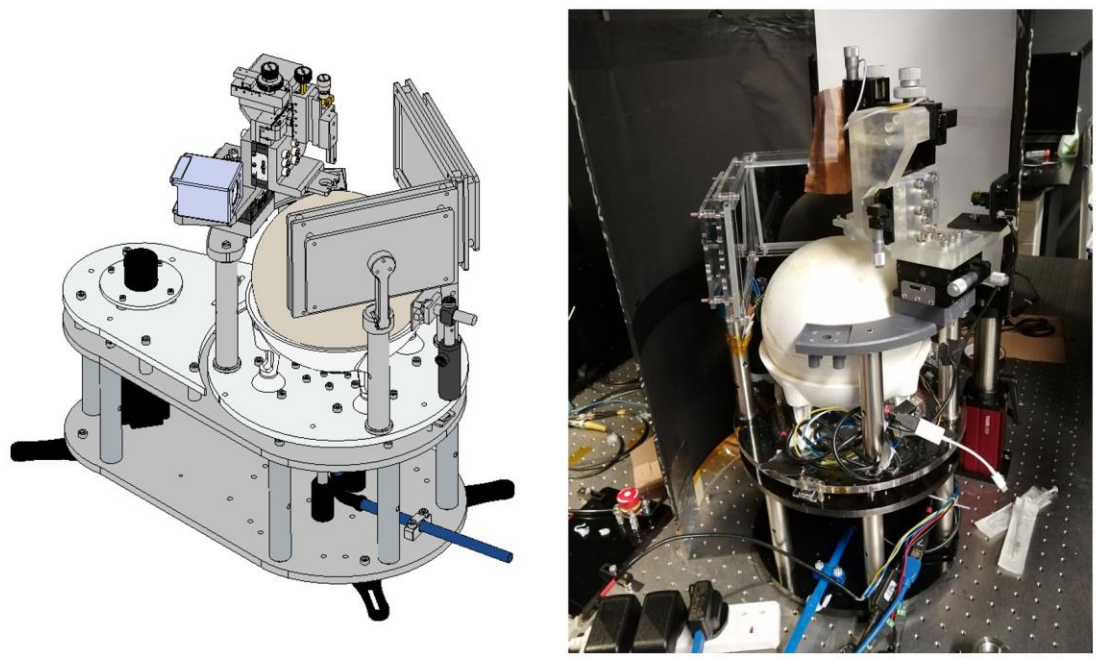

Fig0-Main-Components.png

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Main components of the rotary stage

The device described on the following notes is an open source platform for neuroscientists interested in the study of neural networks that encode the mammal's head angular position. It pretends to be as affordable and customizable possible in order to enable scientists to perform new experiments. This documentation pretends to be an assembly and operation guide for users with some experience in rapid manufacturing and electronics and development boards/microcontroller (such Arduino). In the following notes, the mechanical assembly is explained step by step with graphical images and animations. The main components of the stage are pointed in Figure 1 where there is a rotary platform actuated by a stepper motor using a timing belt. An incremental encoder is coupled with the motor shaft to measure the angular position and there is a hall effect sensor that is used to perform the homing sequence. Compressed air is used to keep a polystyrene sphere without friction inside the sphere holder. The compressed air tube is canalized through the rotary joint and the crossed roller bearing that holds the rotating and non-rotating parts together. The rotary joint enables the electric connections between the rotary platform and the base. The device is intended to be used for behaviour, extracellular recording and optogenetic experiments. The two modes we conceived the device can be used are the closed and open loop modes. In the closed loop mode, the rotation of the sphere on the vertical (yaw) axis is measured using an optical sensor and it is used to generate a motor rotation of an adjustable magnitude (Gain) in the opposite direction. On the other hand, on the open loop, the rotation is independent of the animal's movement.

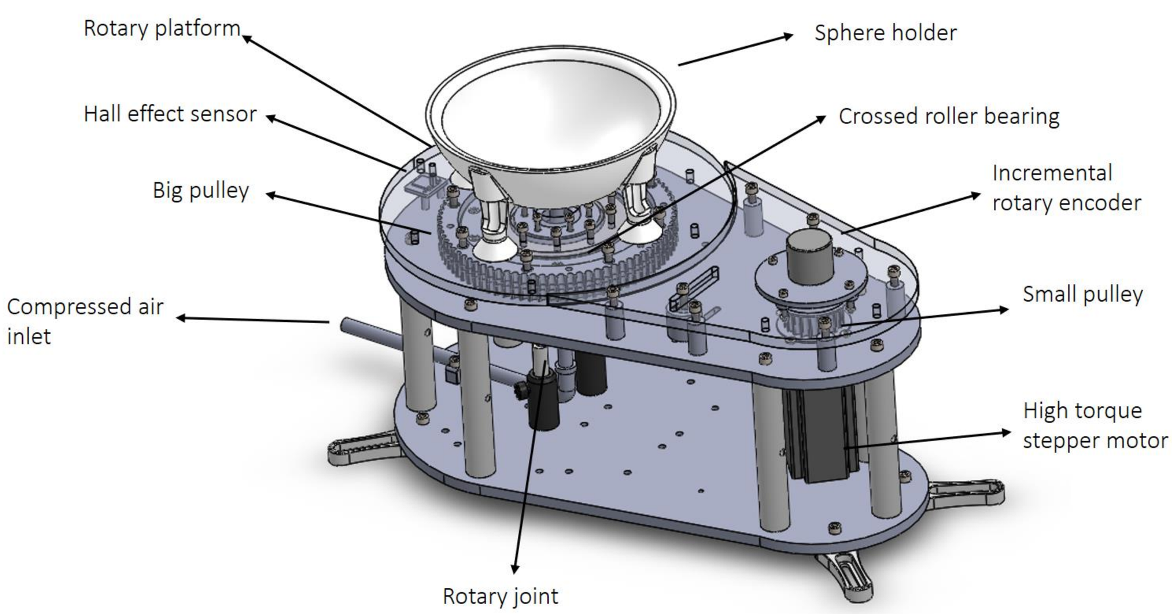


Figure 1: Rotary stage main components.

Fig1-Main-Components.png

Rotary Joint

The rotary joint is the element of the setup that enables communications between the base and the rotary element. The selected model is the Senring UH1256-02-0610-06S, of the UH1256-02 Series [1]. This slip ring has two USB ports that can be used to connect the camera and several power and data wires to connect the different sensors.

Figure 2: Senring UH1256-02-0610-06S Series.

Fig2-Main-Components.png

Crossed roller bearing

The crossed roller bearing is an essential component to get a stable rotation and a strong joint between the static part and de rotation platform. The best axial runout we were able to find was 2-5 µm. Considering the ID >55 mm as an essential requirement of the Rotary Joint, the suitable model for the application is the BRS RU124X. The bearing provides strong joint stability against axial and radial forces and torque.

Figure 3: BRS RU124X Crossed roller bearing.

Fig3-Main-Components.png

DC motor and motor driver

In order to get an approximation of the motor requirements we have estimated the moment of inertia around the vertical axis. For this approximation we have considered two main components: the circular platform and all the elements that are on the platform and the inner ring of the crossed roller bearing. To simplify the approximation, the internal ring of the bearing has been considered as a stainless steel solid part. The friction force of the bearing has not been considered on the equation. Both moments of inertia have been extracted using the mass properties of the Solidworks® CAD software.

$$I_{z\ elements\ on\ the\ platform} = 151799239.83\ g\ mm^2 = 0.1518\ kg\ m^2$$

$$I_{z\ bearing\ inner\ ring} = 3101827.49\ g\ mm^2 = 0.003101827\ kg\ m^2$$

With this value we can make the approximation of the torque needed to accelerate the system using the Newton's 2nd law of rotation M = I α. That give us a theoretical maximum acceleration useful to choose the motor described by the function τ = $0.0026\alpha - 9$^−17 after a numerical simulation.

The Stepper motor selected is a Nema 23 Stepper Motor 3 Nm 4.2A with a DM542A driver [2]:

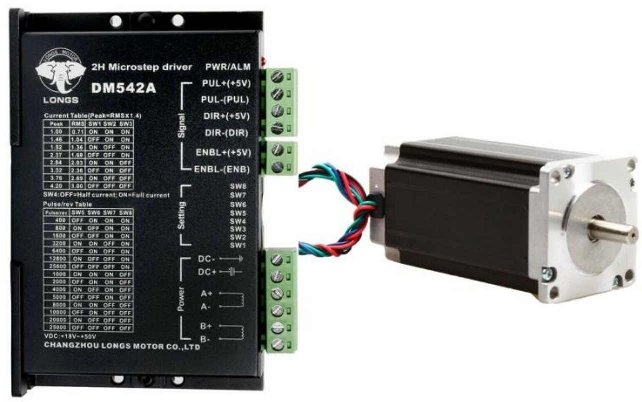


Figure 4: Nema 23 stepper motor and DM542A stepper driver [2].

Fig4-Main-Components.png

Nema 23 Stepper motor main features:

Steps/rev	200
L (mH)	3.2
I_{max} (A)	4.2
V (V)	24
T (N·m)	3
P_{max} (W)	96

Figure 5: Nema 23 stepper motor features [2].

Fig5-Main-Components.png

The Current can be selected using the first four switches of the driver DIP switch:

Output current (A)				
SW1	SW2	SW3	PEAK	RMS
ON	ON	ON	1.00	0.71
OFF	ON	ON	1.46	1.04
ON	OFF	ON	1.91	1.36
OFF	OFF	ON	2.37	1.69
ON	ON	OFF	2.84	2.03
OFF	ON	OFF	3.31	2.36
ON	OFF	OFF	3.76	2.69
OFF	OFF	OFF	4.20	3.00

Figure 6: DM542A stepper driver current options [2].

Fig6-Main-Components.png

The driver has a DIP switch to select the desired micro stepping mode:

1) Micro step resolution is set by SW 5,6,7,8 of the DIP switch as shown in the following table:

SW5	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF	ON	OFF
SW6	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF	ON	ON	OFF	OFF
SW7	ON	ON	ON	OFF	OFF	OFF	OFF	ON	ON	ON	ON	OFF	OFF	OFF	OFF
SW8	ON	ON	ON	ON	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
PULSE/REV	400	800	1600	3200	6400	12800	25600	1000	2000	4000	5000	8000	10000	20000	25000

Figure 7: DM542A stepper driver micro stepping options [2].

Fig7-Main-Components.png

Belt selection

We have adjusted the number of teeth z_p of the big and the small pulley in order to get a gear ratio of 6:1 considering the minimum diameter of the big pulley as the outside diameter of the crossed roller bearing BRS RU124X.

$$d_p = \frac{p\, z_p}{\pi}$$

The diameter of the commercial small pulley with Zp = 36 teeth is 34.38. Once the big and small pulley diameters defined (D and d) the distance between both C has been calculated in order to get the desired commercial length L:

$$L = 2C + \frac{\pi}{2}\,(D + d) + \frac{(D - d)^2}{4C}$$

The number of teeth obtained for the big pulley is 216, and the distance between centers (C) 260 mmThat result guide us to find the according belt for our device.

The timing belt

The size of the belt was calculated considering the outside diameter of the Crossed roller bearing (OD > 165 mm) and the desired gear ratio of 4 which provides the stage of a maximum theoretical value of 12 Nm. In order to calculate the belt parameters, first we consider the maximum width of the belt for our space constrains, which is 20 mm maximum. According with the distance between centers and the pulley diameters, the length of belt needed is 927 mm and the chosen belt width is 15 mm. (Figure 8).

Figure 8: Timing belt HTD3.

Fig8-Main-Components.png

The small pulley

The pulley that is driven by the Nema 23 stepper motor is a 36 teeth HTD3 metal pulley provided by RS Components (Figure 9).

Figure 9: Small pulley.

Fig9-Main-Components.png

Bill of materials

Component	Quantity	Supplier	Reference
Base	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Platform 2 (Rev1)	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Belt cover (Rev1)	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Circular platform	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Spacer	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Encoder holder	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Small pulley (Rev1)	1	RS Components	https://uk.rs-online.com/web/p/belt-pulleys/1465412/
Big pulley (Rev1)	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Belt	1	Ebay	https://www.ebay.co.uk/itm/324243196114?hash=item4b7e6688d2:g:YU8AAOSwIW1fH-nz

Encoder Atachment	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Belt tensor	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Encoder spacer	4	Laser cut part/3D printed	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Cover spacer	6	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Tube guide	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
Rotary joint spacer	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Rotary%20stage
CF175	4	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=CF175#ad-image-0
RS05P Pedestal posts	4	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=RS05P/M
RS150	7	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=RS150/M
TR_50M		Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=TR50/M
PH_50	2	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=PH50/M#ad-image-0
M6 washers	2		
M6 screws	44		
M5 screws	24		
M4 screws	11		https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=248
M3 screws	7		
M6 nuts	9		
M5 nuts	14		
BRS RU124X bearing	1	BRS	http://www.rigbrsbearing.com/product/ru124x-cross-roller-ring/
Rotary Joint	1	Senring	https://www.senring.com/usb-conductive-slip-ring/dual-Channels/uh1256-02.html
Encoder	1	Amazon	https://www.amazon.co.uk/Wisamic-Incremental-Encoder-Dc5-24v-Voltage/dp/B015GYY7X
Hall efect sensor	1	Amazon	https://www.amazon.co.uk/gp/product/B06XHG9CYN/ref=ppx_yo_dt_b_asin_title_o07_s00?
Magnet	1	RS Components	792-4559
Nema 23 Stepper motor	1	Ebay	https://www.ebay.co.uk/itm/Free-Ship-Nema-23-Stepper-Motor-435oz-in-4-2A-Driver-Contro DM542A/273805042516?ssPageName=STRK%3AMEBIDX%3AIT&_trksid=p2060353.m27
Motor driver	1		
M6 threadd inserts			
M4 threaded inserts			
Bearings	2	RS Components	619-0014
Incremental encoder	1	Amazon	https://www.amazon.co.uk/Wisamic-Incremental-Encoder-Dc5-24v-Voltage/dp/B015GYY7X 21&linkCode=df0&hvadid=231995364607&hvpos=&hvnetw=g&hvrand=2855211729431962 d=pla-487280118197&psc=1

Assembly instructions

Start assembling the Acrylic laser cut part “Base” with the Thorlabs RS05P Pedestal posts using M6 screws. That posts are used to attach the rotary stage to the experimental table where the experiments are taking place.

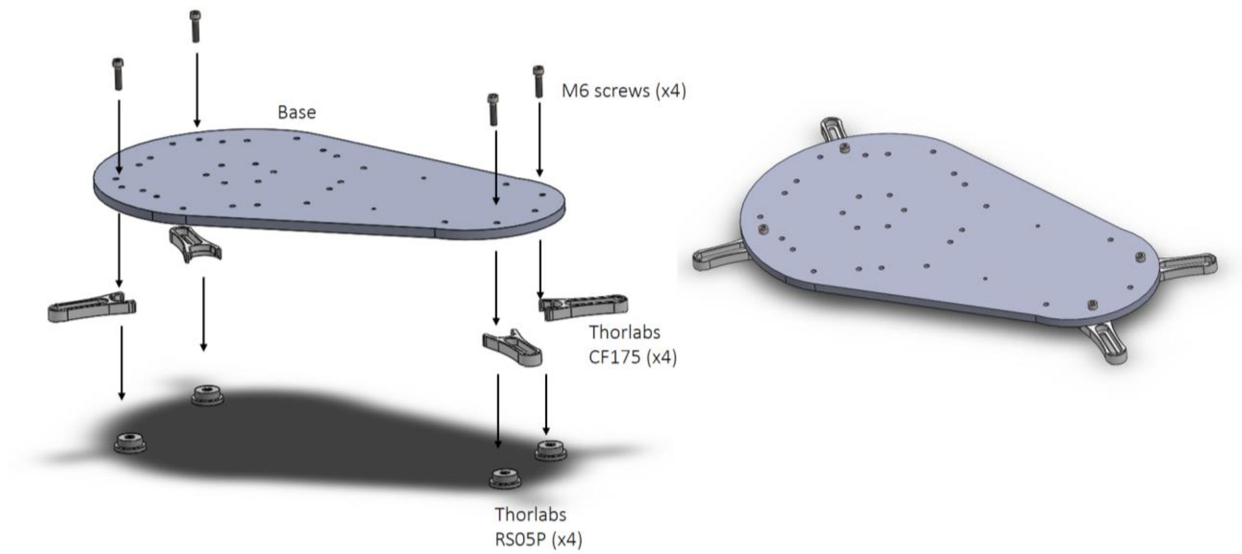


Figure 1: Base assembly.

Fig1-Assembly-Instructions.PNG

Now Insert two M6 screws with their nuts in order to attach the tube guide where the horizontal tube goes through and connects with the elbow. Attach with M6 screws the two Thorlabs PH_50 and the TR_50 with the base.

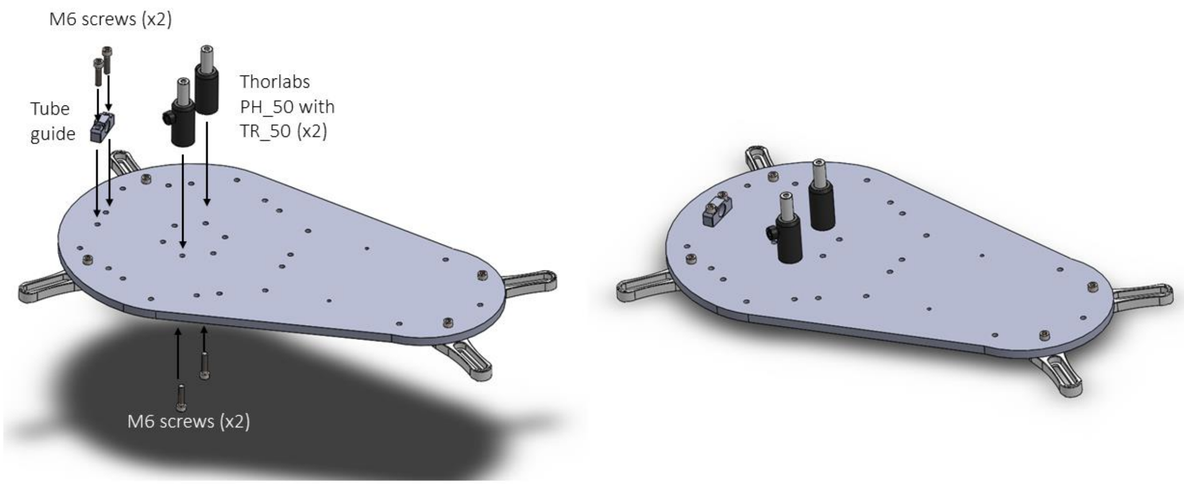


Figure 2: Rotary joint telescopic posts assembly.

Fig2-Assembly-Instructions.PNG

The two Thorlabs PH_50 with the TR_50 are used to hold the rotary joint. In order to attach the rotary joint, you only need two M6 or two M4 with washers depending on the position of the TR_50 (in one side ins M4 in the other is M6). Now toy can install the tubing as well but that can be done at the end of the assembly as well.

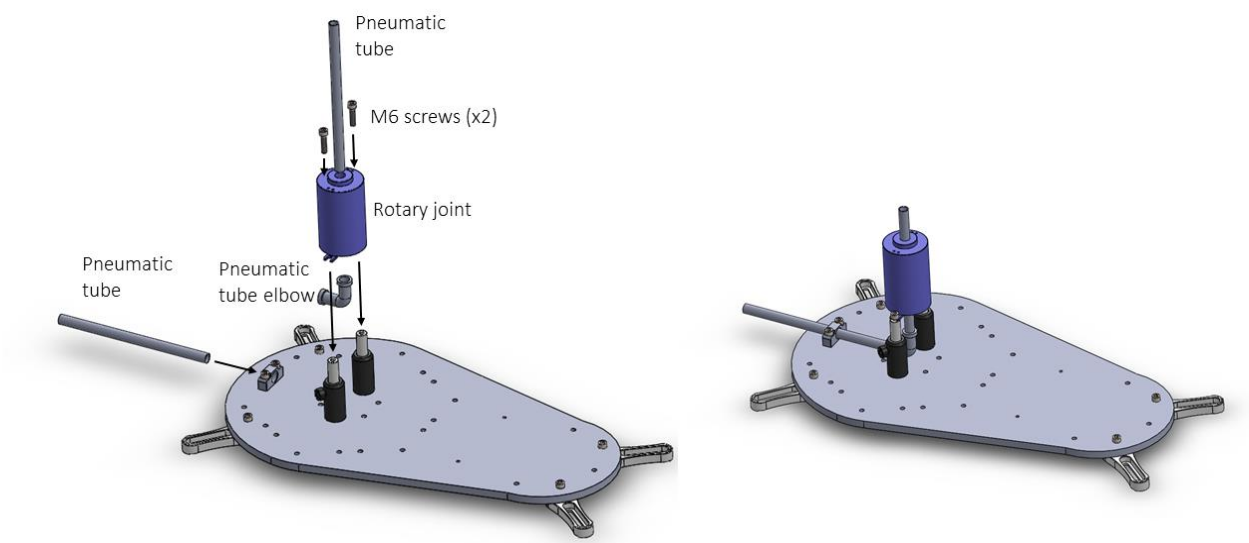


Figure 3: Rotary joint assembly.

Fig3-Assembly-Instructions.PNG

Now attach the seven Thorlabs RS150 posts with the base using M6 screws.

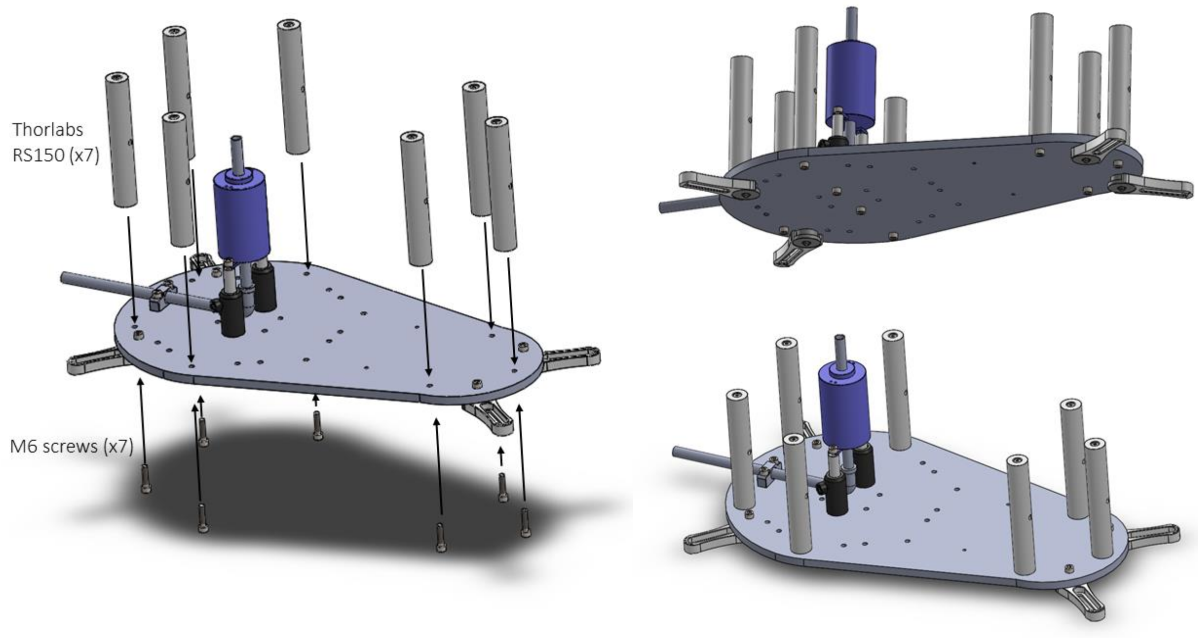


Figure 4: Thorlabs RS150 assembly.

Fig4-Assembly-Instructions.PNG

Once you have the rotary joint spacer 3D printed, insert M3 brass threaded inserts and then cure the part with UV light.

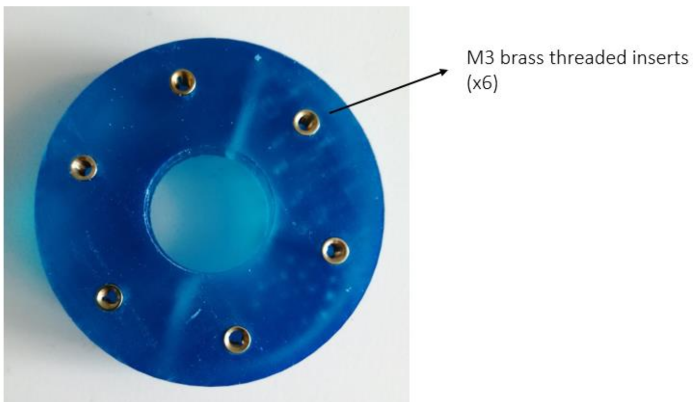


Figure 5: Rotary joint spacer threaded inserts.

Fig5-Assembly-Instructions.PNG

The Rotary Joint spacer is assembled with the rotary joint Using 25 mm length M3 grab screws. These are inserted using the radial holes on the bottom of the part.

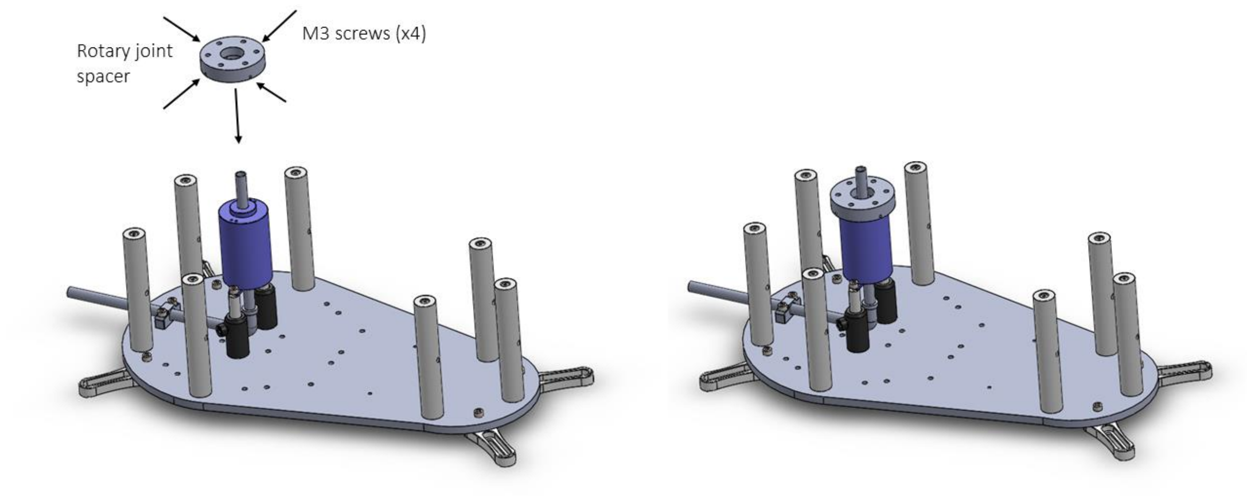


Figure 6: Rotary joint assembly.

Fig6-Assembly-Instructions.PNG

Figure 7: Rotary joint assembly.

Fig7-Assembly-Instructions.PNG

The Crossed roller bearing BRS RU124X must be assembled with the Platform 2 using ten M5 bolts and M5 Nuts.

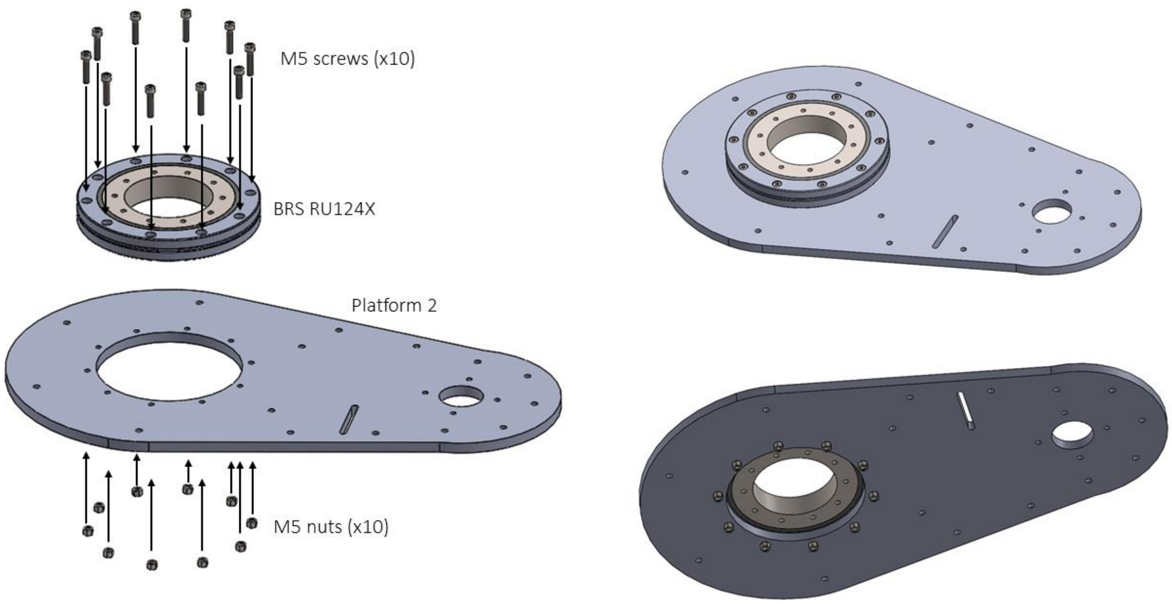


Figure 8: Crossed roller bearing assembled with the Platform 2.

Fig8-Assembly-Instructions.PNG

The manufacturer recommends the following installation method.

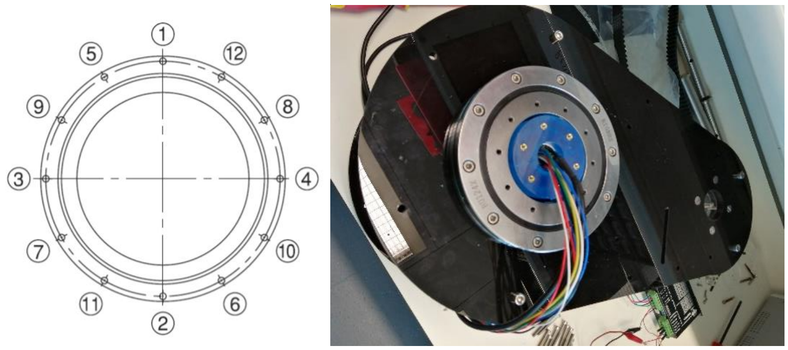


Figure 9: Crossed roller bearing installation method (left) and Cross roller bearing installed (right).

Fig9-Assembly-Instructions.PNG

Warning: On the laser cut part "Platform 2" is reccomended to make the Chamfers for the M4 Countersink screws that will hold the motor. This step is important because the head of the screws have to be at the same level that the surface of the Platform 2, if not they might touch the pulley or the belt.

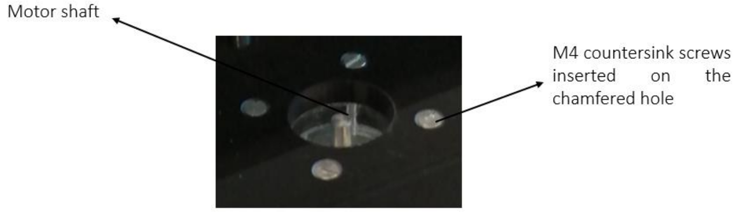


Figure 10: Detail of the countersink screws at the same level that the surface.

Fig10-Assembly-Instructions.PNG

Insert the four M4 screws with their nuts to hold the Nema 23 stepper motor with the motor spacer.

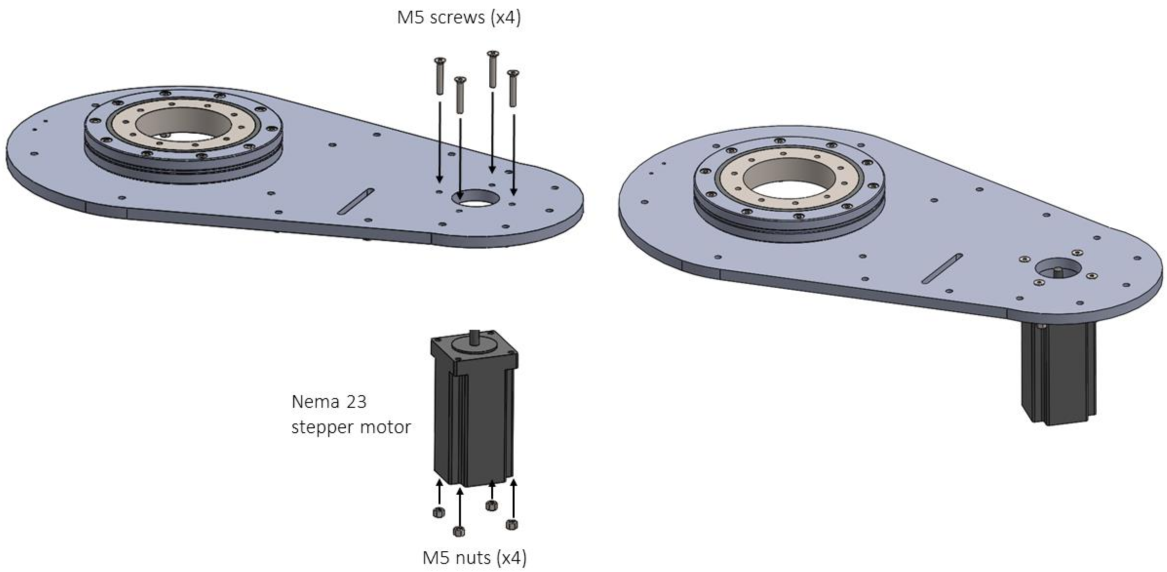


Figure 11: Motor assembly.

Fig11-Assembly-Instructions.PNG

The Big pulley can be laser cut as shown in Figure 12, it is composed by six layers of acrylic thickness (2 x Big pulley rev1 (1).dxf in 5 mm thickness, 1 x Big pulley rev1 (3).dxf in 5 mm thickness, 2 x Big pulley rev1 (3).dxf in 3 mm thickness and 1 x Big pulley rev1 (2).dxf in 3 mm thickness). The threaded inserts are attached like in the previous version. In this case we recommend to heat them with the soldering iron until they melt the plastic around and go through the different layers. Alternatively, there is an STL file to 3D print the pulley in one single piece. We haven’t tried that option yet. As shown in figure 12 the threaded inserts can be inserted heating them with the soldering iron and melting the plastic around. It is recommended to insert a coupled using the external thread in order to get good alignment of the pulley teeth.

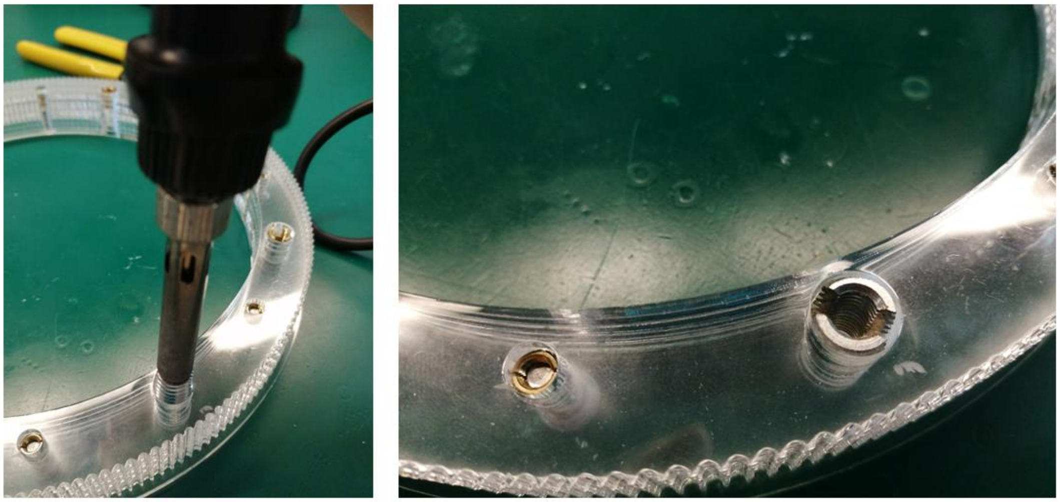


Figure 12: Big pulley assembly (left) threaded inserts (right).

Fig12-Assembly-Instructions.PNG

After laser cutting the Circular platform, you have to glue a small 5 mm Neodymium magnet. One of the surfaces of the magnet has to be coincident with the bottom surface of the platform. The magnet is there to interact with the Hall effect sensor of the bottom and change the state to high or low to complete the homing position. Also is essential to make the chamfer on the outside holes for the countersink screws.

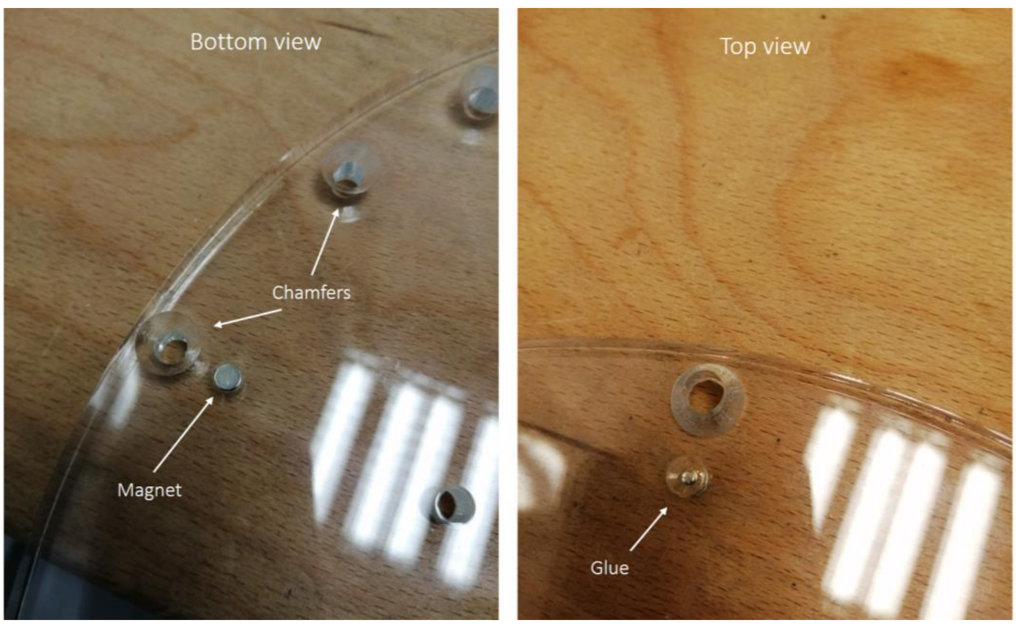


Figure 13: Magnet gluing and chamfers.

Fig13-Assembly-Instructions.PNG

Insert eight M6 screws to attach the Circular platform with the big pulley using the threaded inserts thread.

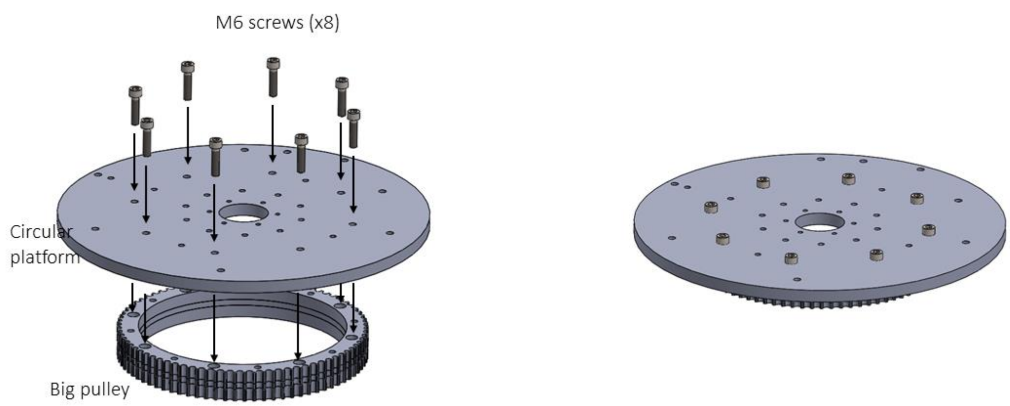


Figure 14: Circular platform and big pulley assembly.

Fig14-Assembly-Instructions.PNG

Assemble the Base with the Platform 2 using 7 M6 screws.

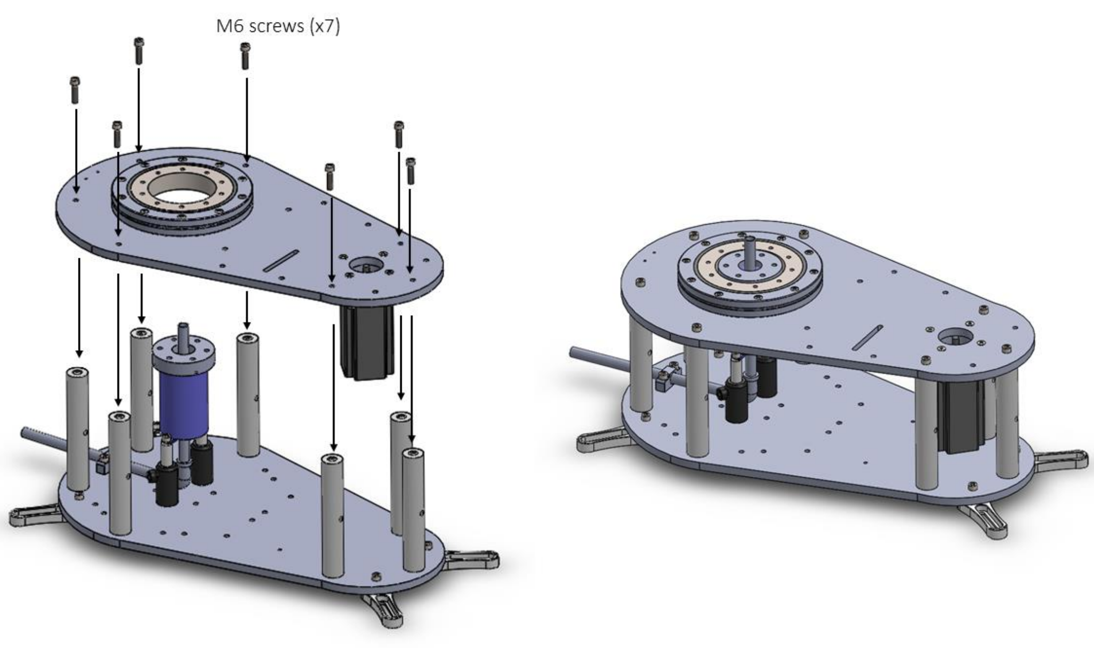


Figure 15: Base and Platform 2 assembly.

Fig15-Assembly-Instructions.PNG

Now it is time to assemble the Hall Effect sensor that will be used for the homing sequence. For that, two M3 screws are needed and two Hall effect spacers with the Hall Effect holder.

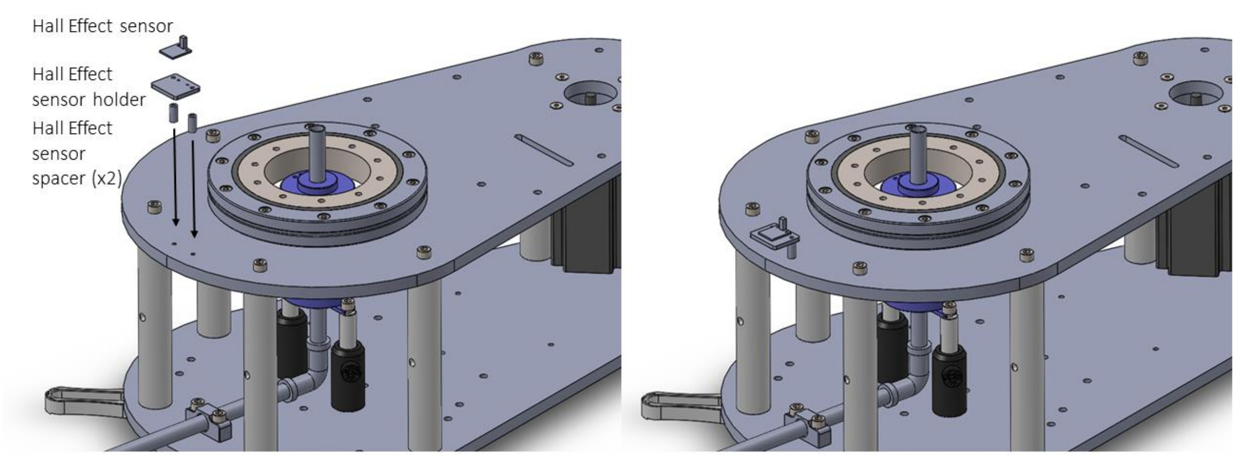


Figure 16: Hall Effect sensor assembly.

Fig16-Assembly-Instructions.PNG

Now it is time to assemble the Hall Effect sensor that will be used for the homing sequence. For that, two M3 screws are needed and two Hall effect spacers with the Hall Effect holder.

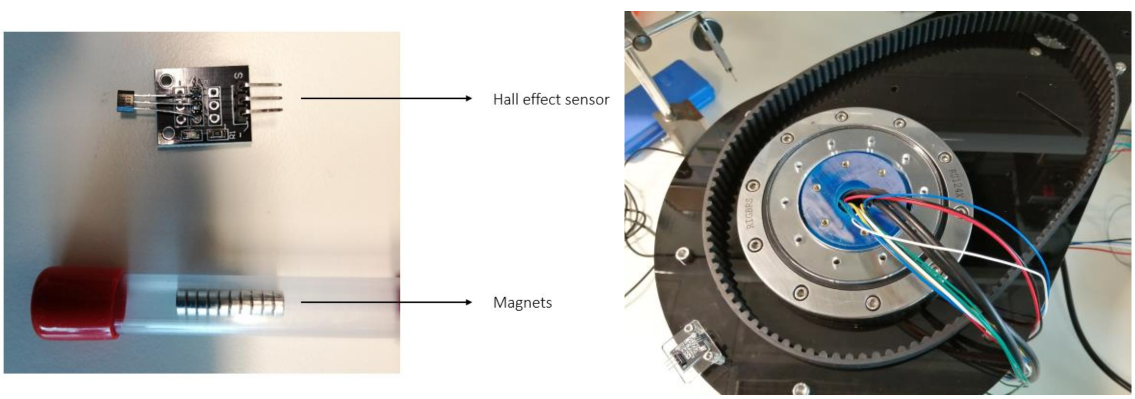


Figure 17: Hall effect sensor placement.

Fig17-Assembly-Instructions.PNG

In order to assemble the Circular platform, you have to place the spacer in contact with the inner ring of the bearing and then place the circular platform previously assembled with the big pulley on the spacer and use then M5 screws also installed as in the first step of the bearing. After that you can use the Thorlabs PH_50 and the TR_50 to adjust the height of the rotary joint spacer until this one makes contact with the Circular platform surface. Once it makes contact you can insert six M4 screws to attach it.

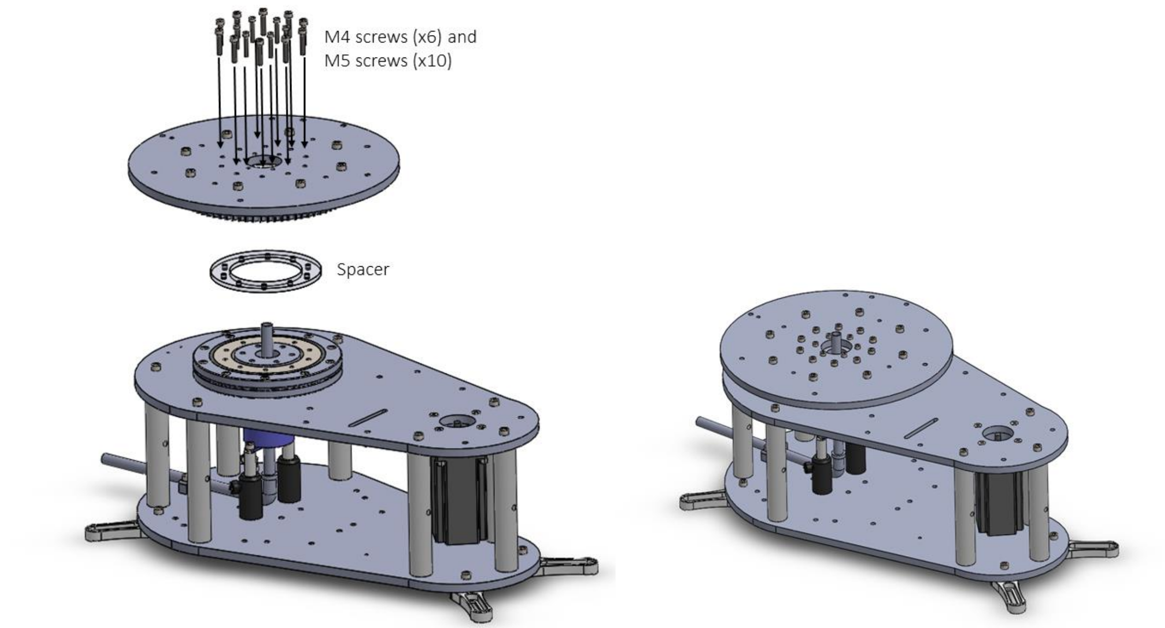


Figure 18: Circular platform assembly.

Fig18-Assembly-Instructions.PNG

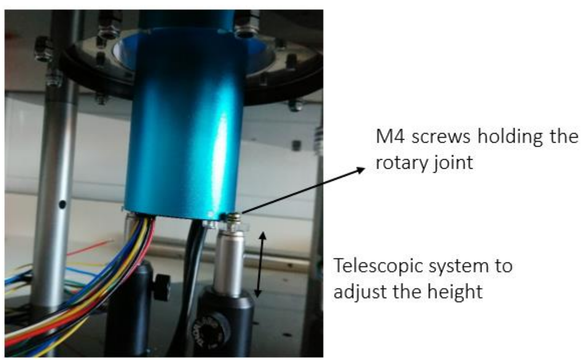


Figure 19: Adjustment of the Rotary joint height.

Fig19-Assembly-Instructions.PNG

The shaft of the Motor is 8 mm in diameter and the inner diameter of the small pulley (https://uk.rs-online.com/web/p/belt-pulleys/1465412/) is 6 mm. The inner diameter of the pulley has to be increased to 8 mm with a vertical drilling machine/milling machine (Figure 20). After that a second hole with 3.3 mm diameter (3.3 mm drill bit) is needed to add the screw that prevents from the pulley to rotate around the motor shaft. Then, using an M4 tap toolkit the thread must be made. For that step, the use of a vice is recommended to hold the pulley in vertical and horizontal positions while drilling. In order to connect the encoder shaft with the pulley, the encoder attachment must be 3D printed and two extra 2.5 mm holes must be drilled at the top of the pulley. Then, an M3 thread must be made using the M3 tap tool.

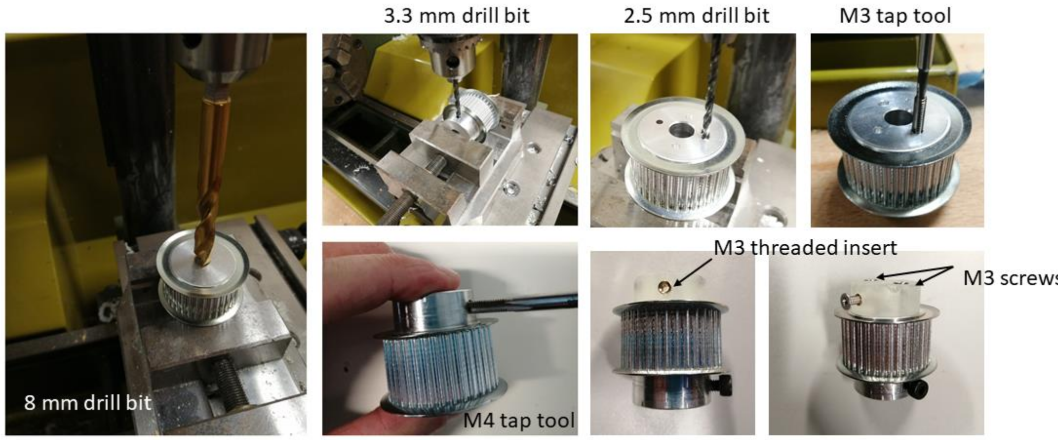


Figure 20: Small pulley.

Fig20-Assembly-Instructions.PNG

The pulley can be assembled before or after attaching the motor with the platform 2 (Figure 21).

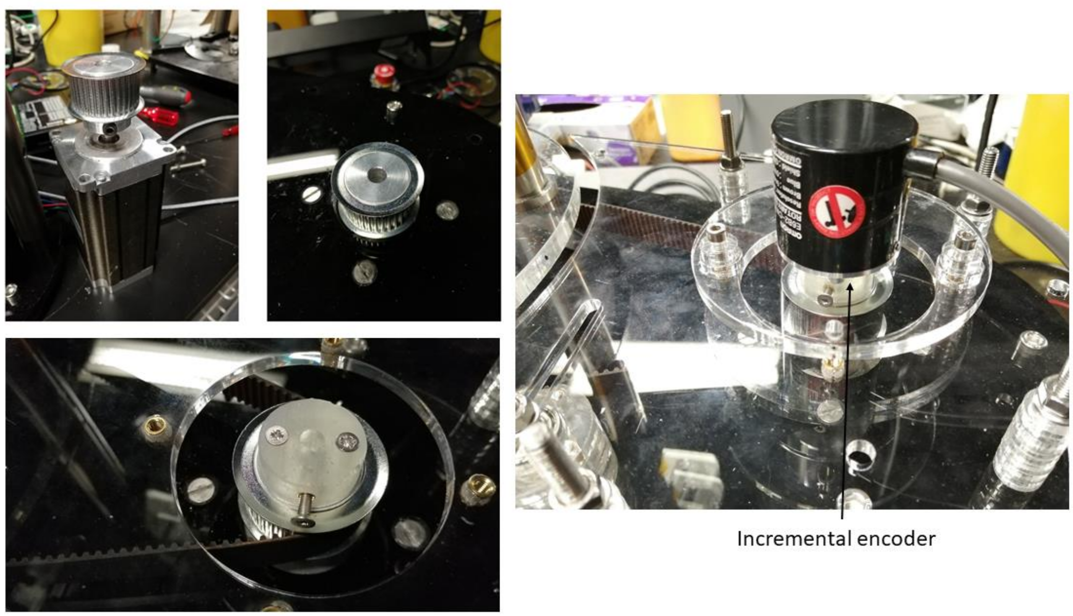


Figure 21: Metal small pulley modified

Fig21-Assembly-Instructions.PNG

The belt has to be enveloping the small pulley when you insert it on the motor shaft. You will feel a “High” tension when pulling the belt since it is rigid.

Warning: Remember to put the flat part of the motor shaft oriented in a comfortable position to make pressure with the pulley M4 screw afterwards.

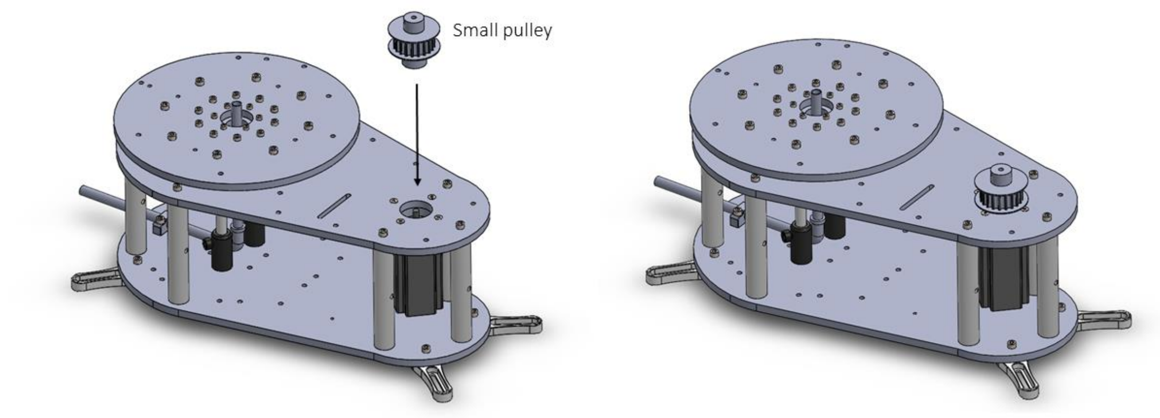


Figure 22: Small pulley with motor shaft assembly.

Fig22-Assembly-Instructions.PNG

The big pulley is attached with the Circular platform with M6 screws and then attached with the crossed roller bearing using M5 screws.

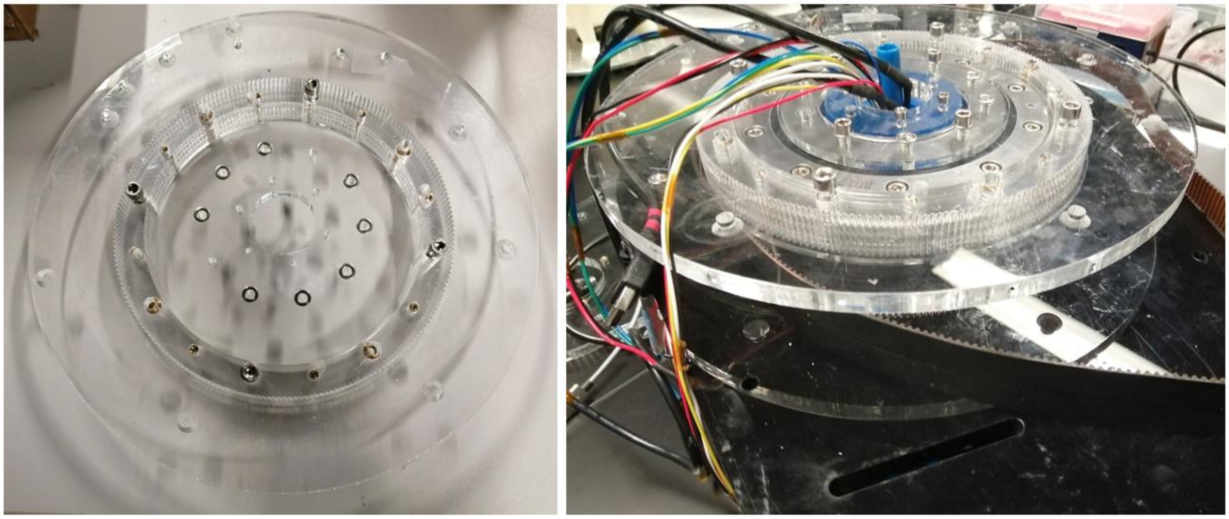


Figure 23: Assembly of the big pulley with the platform and both with the crossed roller bearing using M5 screws.

Fig23-Assembly-Instructions.PNG

Three M3 screws are used to attach the Encoder holder with the encoder.

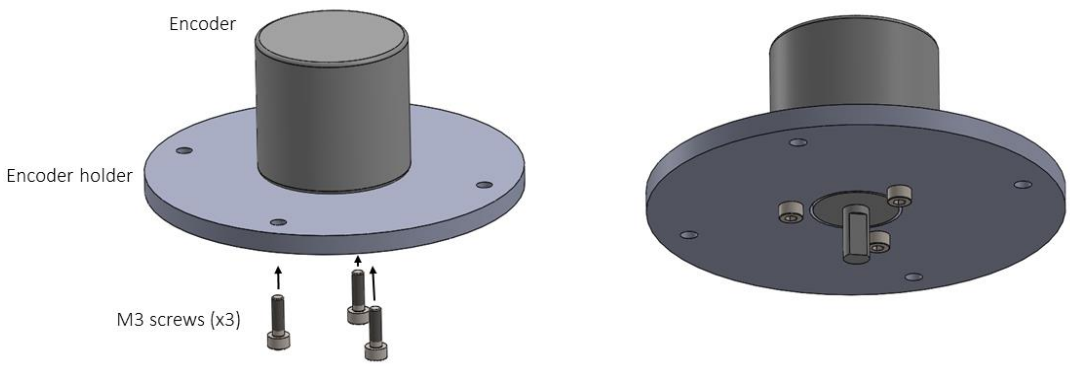


Figure 24: Encoder holder and encoder assembly.

Fig24-Assembly-Instructions.PNG

Once the belt cover part is cut with the laser, four brass M4 threaded inserts must be inserted on the holes heaing them with the soldering iron or just by applying pressure.

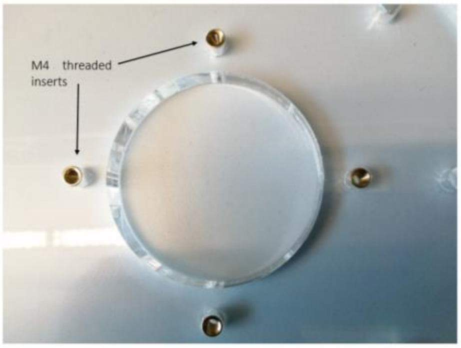


Figure 25: M4 threaded inserts on the belt cover.

Fig25-Assembly-Instructions.PNG

Now four M4 screws can be inserted from the top placing the spacers coincident with the holes.

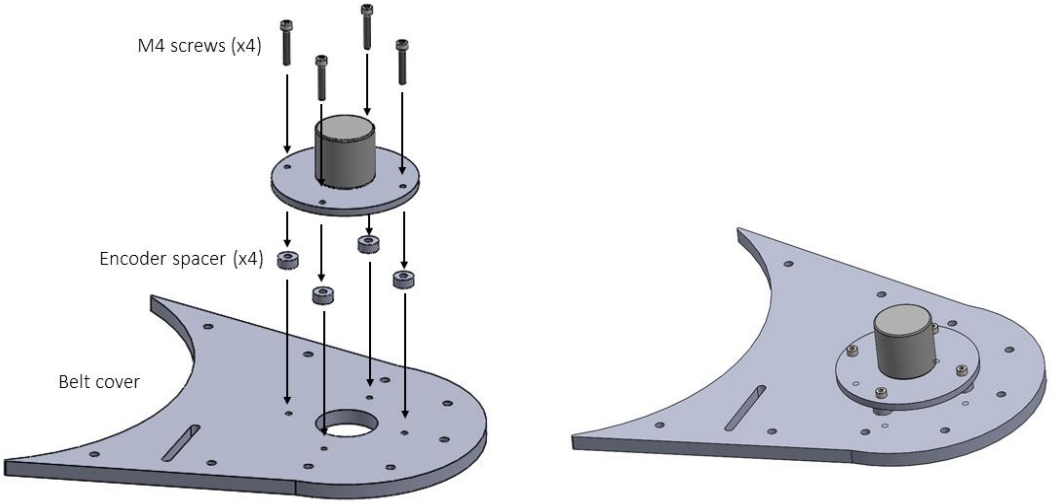


Figure 26: M4 threaded inserts on the belt cover.

Fig26-Assembly-Instructions.PNG

The belt cover can now be installed using M6 screws, nuts and the cover spacers. After that, the encoder shaft needs to be put in contact with the M4 grab screw of the top of the pulley.

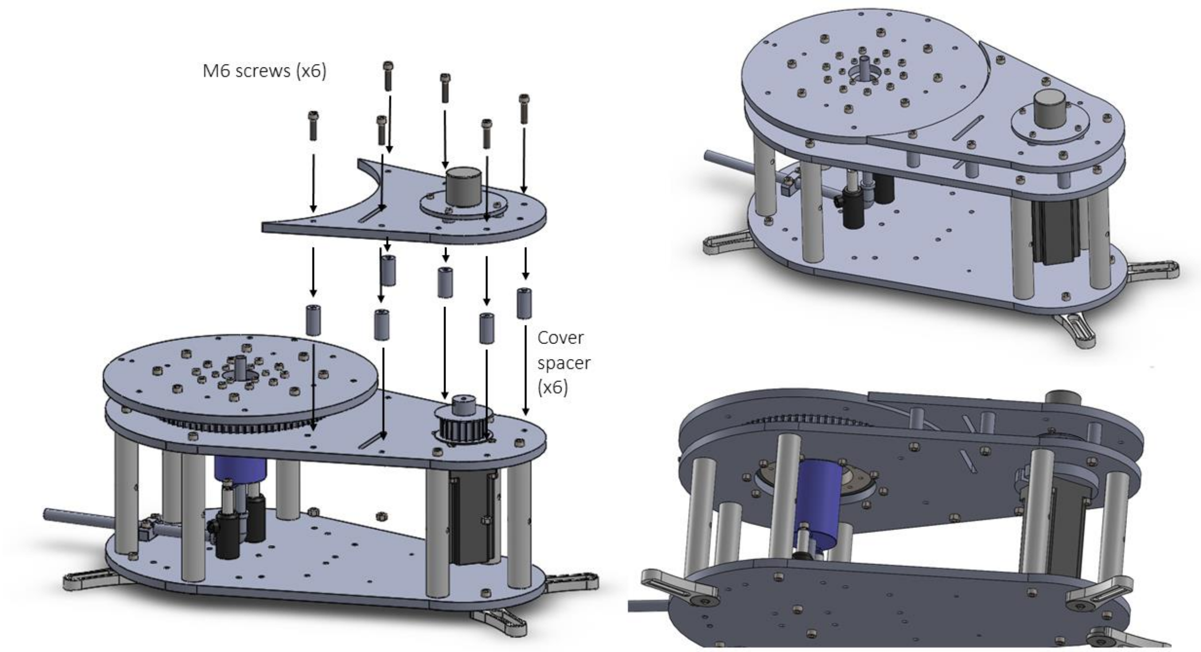


Figure 27: Belt cover assembly.

Fig27-Assembly-Instructions.PNG

Two ball bearings are inserted on the belt tensor and one M6 screw is used to install the belt tensor in the guide. Use four washers to get a good fit on the inside and outside of the screw with the two sides of belt cover and Platform 2.

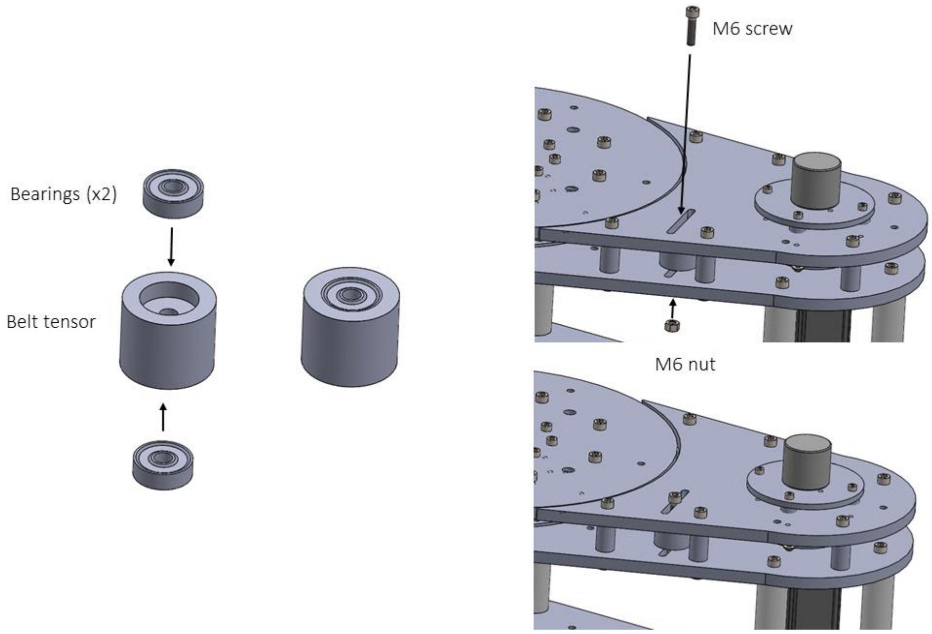


Figure 28: Belt tensor assembly.

Fig28-Assembly-Instructions.PNG

Detail of the two ball bearings.

Figure 29: Belt tensor assembly.

Fig29-Assembly-Instructions.PNG

Now adjust the tension of the belt. After that check that the belt is not touching the bottom or the top surfaces.

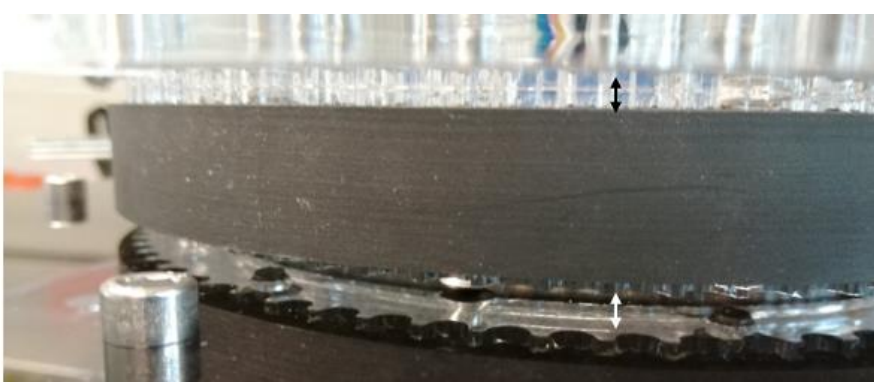


Figure 30: Space on both sides of the belt.

Fig30-Assembly-Instructions.PNG

The sphere holder has to be attached with four M6 screws.

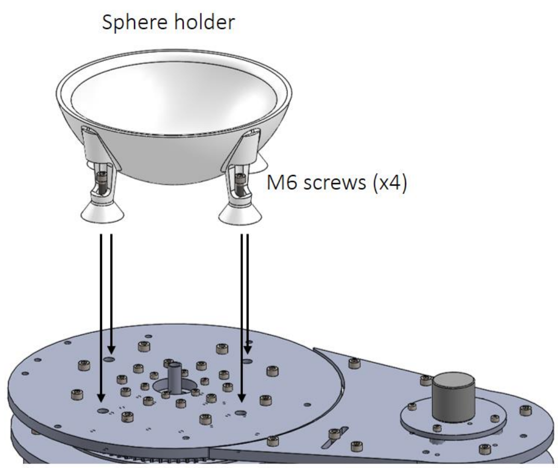


Figure 31: Sphere holder assembly.

Fig31-Assembly-Instructions.PNG

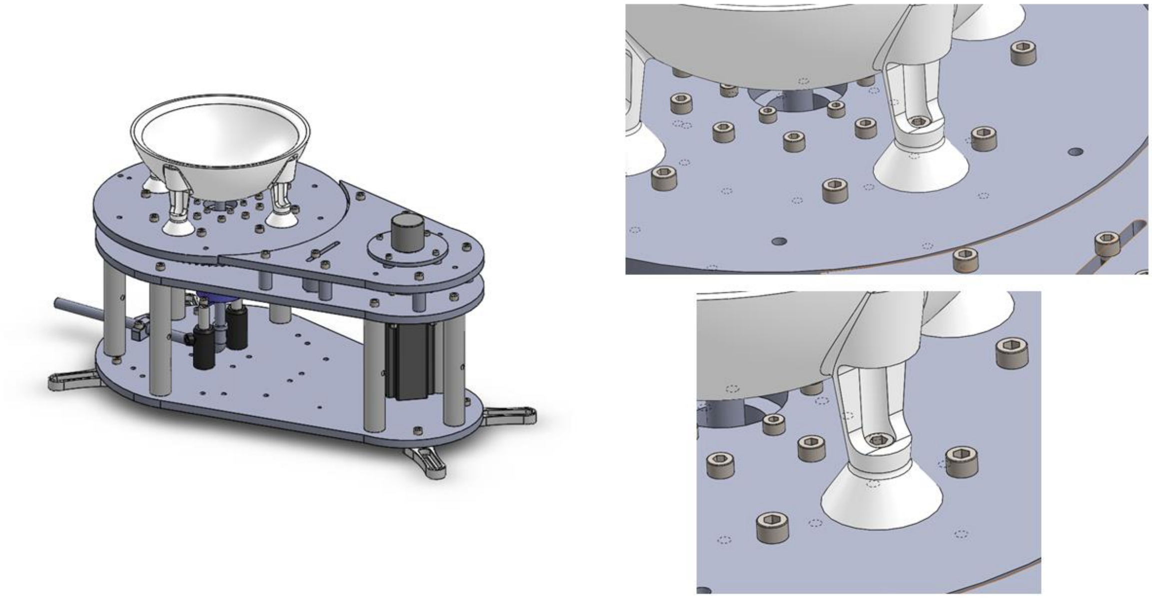


Figure 32: Stage completed.

Fig32-Assembly-Instructions.PNG

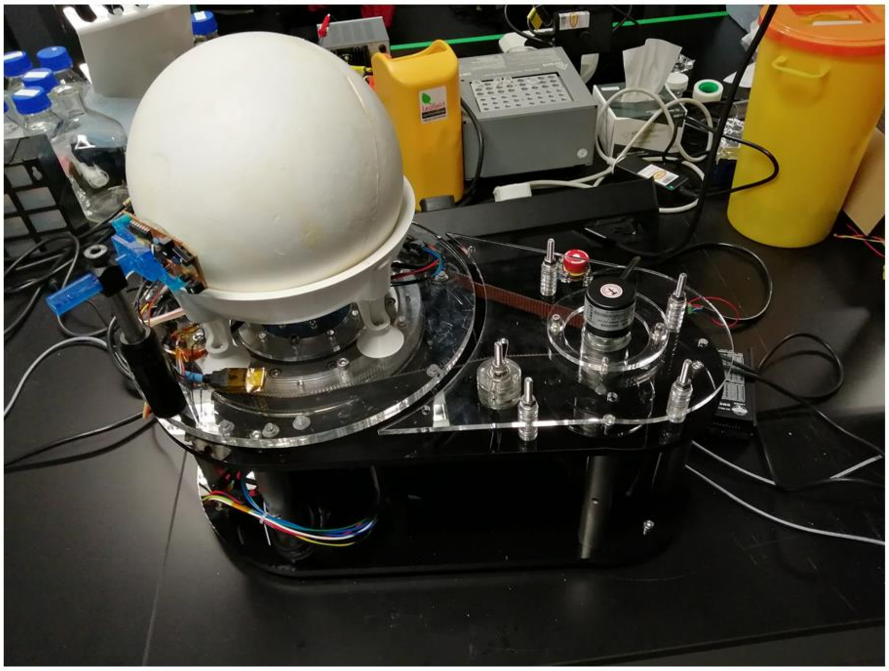


Figure 33: Completed assembly.

Fig33-Assembly-Instructions.PNG

Schematics and electrical connections

The device is controlled using a custom PCB which connects the Teensy 3.5 development board with the DM542 stepper motor driver. The board is supplied at 24V and it has the voltage regulators to provide a 5V power supply to the Teesny. I also have two bi-directional logic level shifters (5-3.3V) so up to eight 5V signals can be converted to 3.3V. I also has two BNC connectors connected to the two Teensy DAC, SPI pins (3.3V) and some extra digital pins at 3.3V.

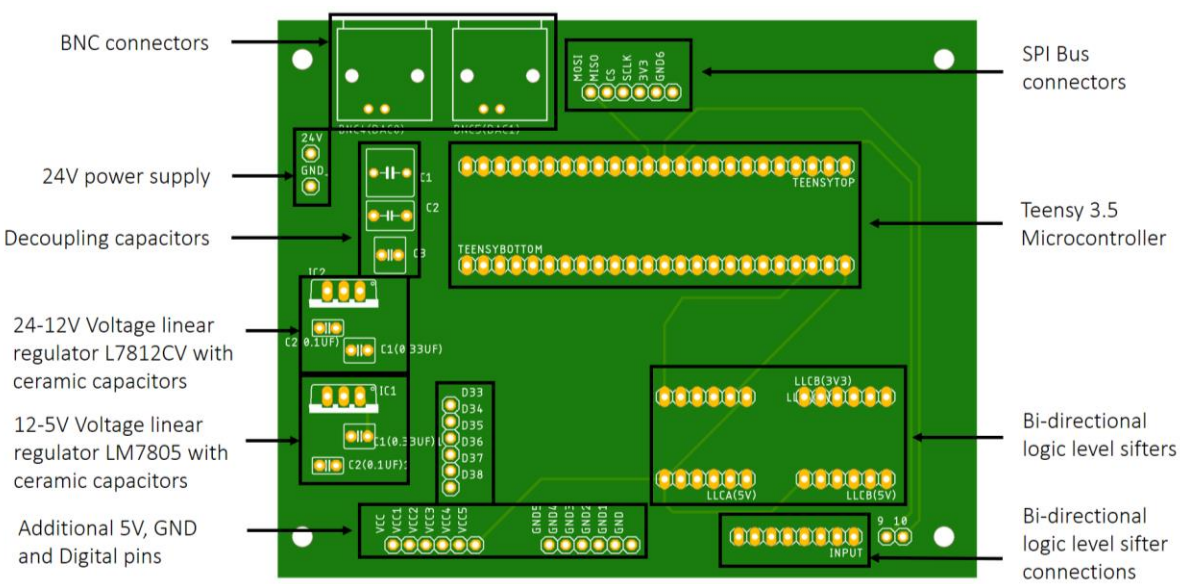


Figure 1: PCB description.

Fig1-Electrical-Connections.PNG

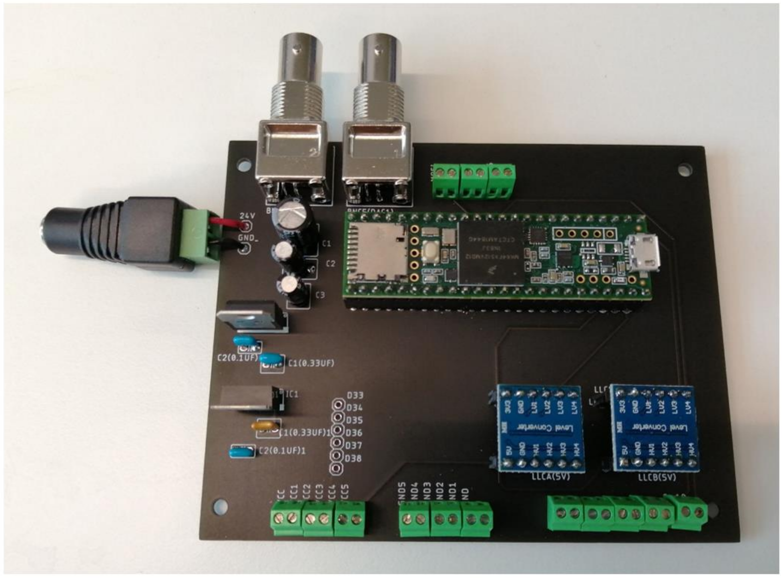


Figure 2: PCB with the components soldered.

Fig2-Electrical-Connections.PNG

A simplified version of the connections of the setup is shown in Figure 3:

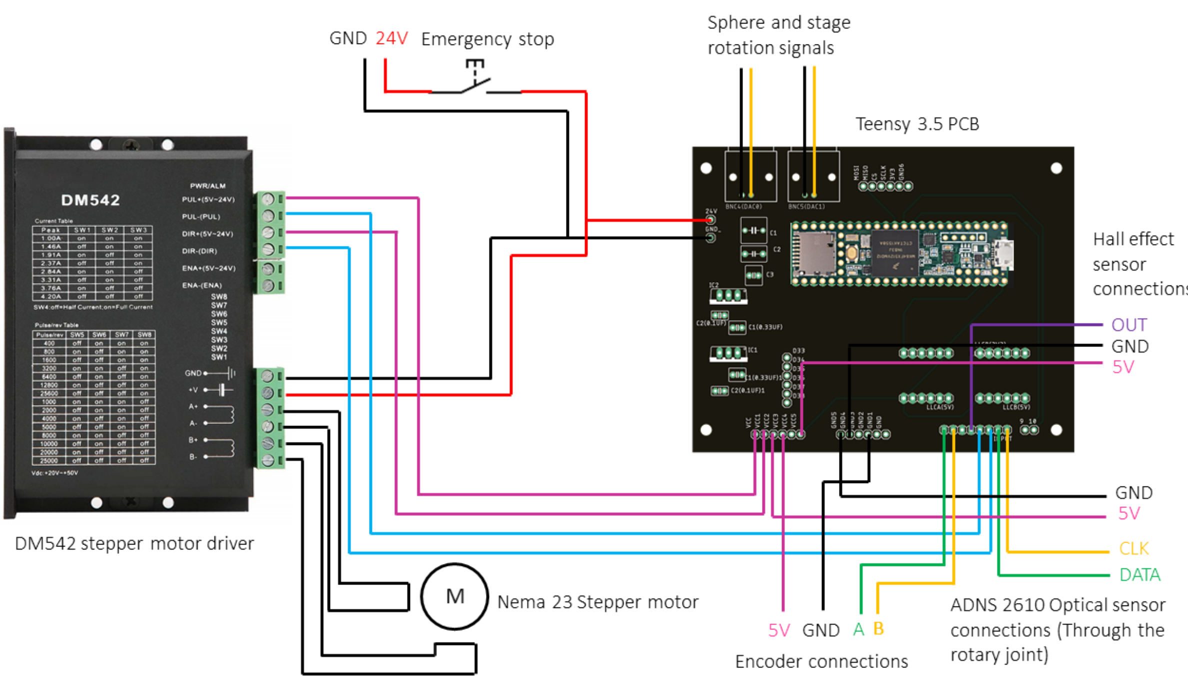


Figure 3: Setup connections.

Fig3-Electrical-Connections.PNG

Recommendation: For electrical recordings put the electronics ½ meter apart from the rotary stage.

The emergency stop opens the 24V power supply circuit, the whole experimental device is disconnected if it is pressed.

Warning: Before soldering the Emergency stop pins check the continuity between and the logic operation between pins. If the button is pressed, the circuit must be open.

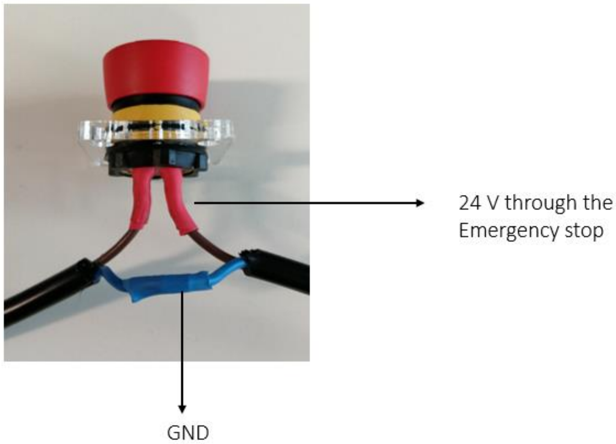


Figure 4: Emergency stop soldering.

Fig4-Electrical-Connections.PNG

Component	**Quantity**	**Supplier**	**Reference**
PCB	1	-	https://github.com/atranvan/vestibular_setup/tree/Files/Electron
Logic Level Converter Module	2	Amazon	https://www.amazon.co.uk/gp/product/B0148BLZGE/ref=ppx_
Teensy 3.5	1	PJRC	https://www.pjrc.com/store/teensy35.html
BNC connectors	2	RS Components	https://uk.rs-online.com/web/p/coaxial-connectors/7100453/
12V voltage regulator L7812CV	1	RS Components	https://uk.rs-online.com/web/p/linear-voltage-regulators/79313
5V voltage regulator LM7805	1	RS Components	https://uk.rs-online.com/web/p/linear-voltage-regulators/79680
Electrolytic capacitor 330 uF 25V	1	Ebay	
Electrolytic capacitor 47uF 50V	1	Ebay	https://www.ebay.co.uk/c/16029438608?iid=303554359855
Electrolytic capacitor 1uF 50V	1	Ebay	
Ceramic capacitor 100 nF 25V	2	RS Components	https://uk.rs-online.com/web/p/mlccs-multilayer-ceramic-capac
Ceramic capacitor 330 nF 25V	2	RS Components	https://uk.rs-online.com/web/p/mlccs-multilayer-ceramic-capac
Standard female pin headers	6	Amazon	https://www.amazon.co.uk/Aussel-Pieces-Breakaway-Connecto 20PCS/dp/B01M69EA9O/ref=sr_1_3?dchild=1&keywords=fer
Emergency stop	1	RS Components	https://uk.rs-online.com/web/p/emergency-stop-push-buttons/4
Hall effect sensor	1	Amazon	https://www.amazon.co.uk/gp/product/B06XHG9CYN/ref=ppx

Stepper driver configuration

The configuration of the motor driver for the position control is the corresponding to 25,000 steps per revolution on the motor shaft (150,000 steps per revolution on the rotary table):

Current Switches				Step resolution switches			
SW1	SW2	SW3	SW4	SW5	SW6	SW7	SW8
OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

In order to control the closed loop response, we have explored how the different configurations of micro stepping of the driver DM542A match with the internal units of the optical motion sensor. In the case of the ADNS 2610, the measured average number of internal units per revolution is approximately 9,391 and therefore the micro stepping configuration of 25,000 steps per revolution appears to be one of the best.

The reason why we have chosen this configuration is because we have evaluated the relationship between the number of steps and the sensor internal units in each possible micro stepping configuration. The number of steps on the big pulley is 150,000 steps with the gear ratio of 6 between small and big pulley. Therefore, the number of steps per each optical sensor unit is 15.97steps. Also this is the most silent configuration and helps reducing vibrations on the platform that could affect the extracellular recordings.

To efficiently control the stepper motor we have used the TeensyStep library [4] which can control multiple stepper motors precisely at high speeds (300,000 steps/s) and accelerations (500,000 steps/s^2). We have implemented a proportional control between the angle measured on the Styrofoam sphere as a set point and the angle of the stepper motor measured from the internal counter of the stepper object using the method stepper.getPosition() [5]. The Proportional control uses the method controller.overrideSpeed() in order to change the rotational speed on the fly.

$$delta = (Setpoint - stepper.getPosition()) * \left(\frac{kp}{P_{Interval}}\right)$$

The Encoder can be used to record the position separately or implement a close loop control using the encoder as a position reference.

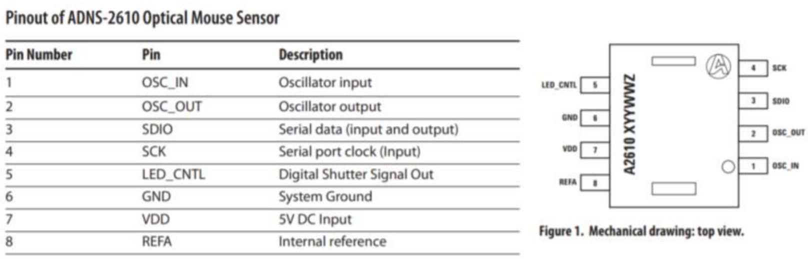
The range of speed and acceleration we have tested with the rotary stage vary from 20 to 100 deg/s and 200 to 1200 deg/s^2.

The main loop() execution period on the Teensy 3.5 at 120 MHz is approximately 270 µs therefore the program execution frequency is higher than 3 kHz where the position of the sensor is evaluated and sent to the stepper motor.

If the speed is increased the system will tent to overshoot compromising the and the proportional constant (kp) of the control algorithm might have to be adjusted in order to get a better performance. That said, with the kp you will find on our code examples we always got good results.

Optical motion sensors

The sensors to measure the position of the sphere are two PCB boards based on the Avago Technologies ADNS-2610 [6] optical flow sensor and extracted from the Logitech M-SBF96 PS2 computer mouse [7]. This sensor presents high reliability for speeds under 30.5 cm/s. Also has a register that outputs the SQUAL value, a reference of the quality of the surface. This makes the calibration process more simple. The PCB and the lens are attached to a 3D printable structure which is assembled with 3 Thorlabs components.



Pinout of ADNS-2610 Optical Mouse Sensor

Pin Number	Pin	Description
1	OSC_IN	Oscillator input
2	OSC_OUT	Oscillator output
3	SDIO	Serial data (input and output)
4	SCK	Serial port clock (Input)
5	LED_CNTL	Digital Shutter Signal Out
6	GND	System Ground
7	VDD	5V DC Input
8	REFA	Internal reference

Figure 1: Pinout of the ADNS-2610 [6].

Fig1-Optical-Motion_Sensors.PNG

Assembly instructions

Table 1: Bill of materials (For each sensor).

Component	Quantity	Supplier	Reference
Optical mouse	1	Ebay	https://www.ebay.co.uk/itm/HP-PS2-Optical-Mouse-for-Desktops-Laptops-417966-001/272643457275?ssPageName=STRK%3AMEBIDX%3AIT&_trksid=p2060353.m2749.l2649
Sensor holder	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Optical%20sensor%20ADNS%202610
PH75_M	1	Thorlabs	
RA180_M	1	Thorlabs	
TR75V_M	1	Thorlabs	
M3 x 6 mm	2	RS Components	137-720 RS PRO M3 x 6mm Hex Socket Set Screw Plain Stainless Steel
M3 threaded insert	2	RS Components	278-534 RS PRO, M3 Brass Threaded Insert diameter 4mm Depth 4.78mm

In order to use the mice sensors, the PCB must be removed from the optical mouse and the VDD, GND, SCK and SDIO must be soldered with wires to be connected to the microcontroller with the microcontroller internal 5V power supply (Figure 2).

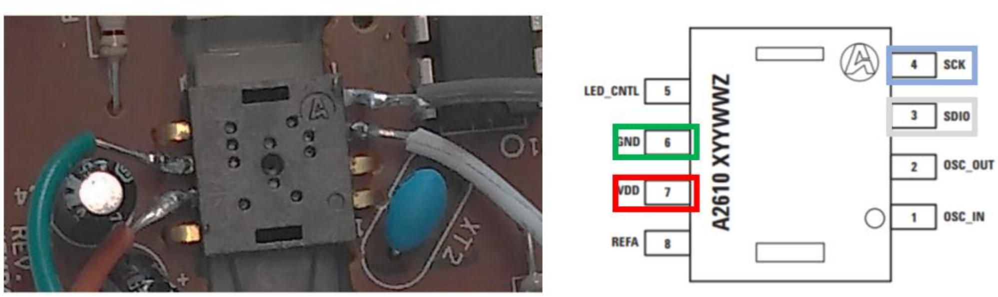


Figure 2: Soldered pins on the ADNS-2610.

Fig2-Optical-Motion_Sensors.PNG

All the 3D printable parts must be printed, the parts have been designed to be printed optimally with an Objet 30 (Polyjet resin printer), also have been printed with a Form 2 (SLS resin printer). The materials used are the Vero gray resin and the Clear V4 resin with the Objet 30 and the Form 2 respectively. For both printers the settings have been the default settings.

Insert the two M3 brass threaded inserts by applying pressure. Then attach the sensor on the sensor holder using 2 M3 screws. Follow the instructions on Figure 3 to assemble the three Thorlabs components with the Sensor holder.

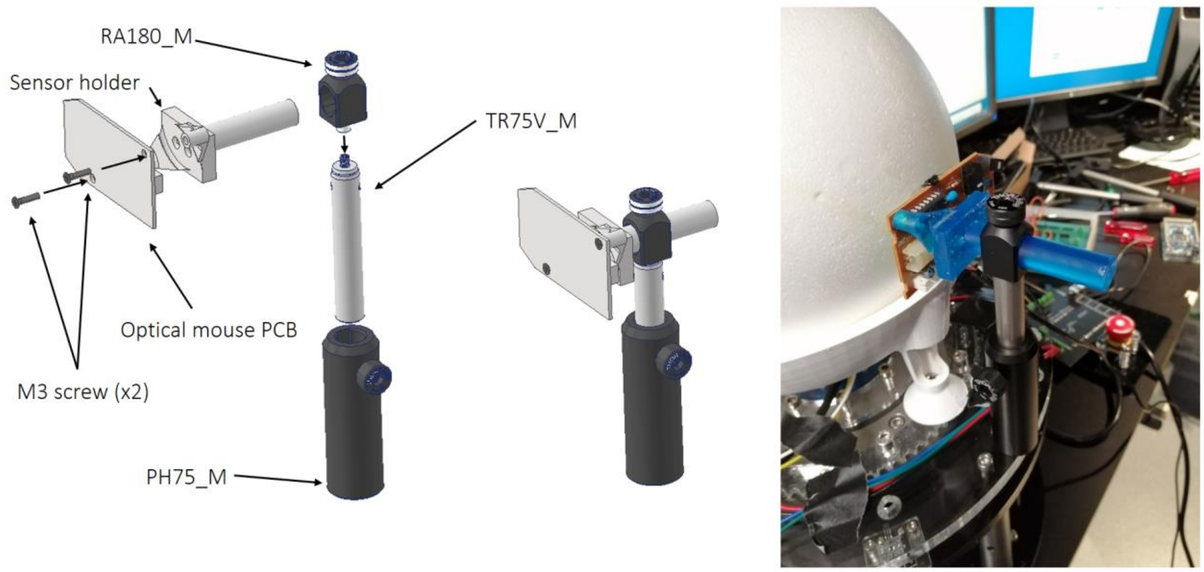


Figure 3: Optical sensor assembly.

Fig3-Optical-Motion_Sensors.PNG

The lens must be glued to the PCB in the correct position, with the lens aligned with the optical flow sensor.

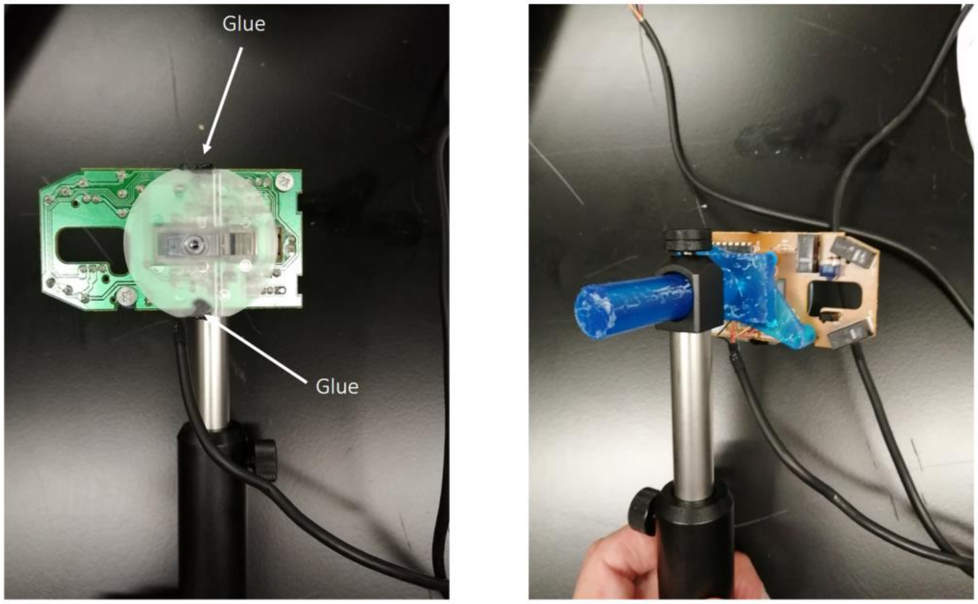


Figure 4: ADNS-2610 glued with the lens.

Fig4-Optical-Motion_Sensors.PNG

Attach the whole assembly on the rotary stage platform where the magnet at 0 degrees' reference is.

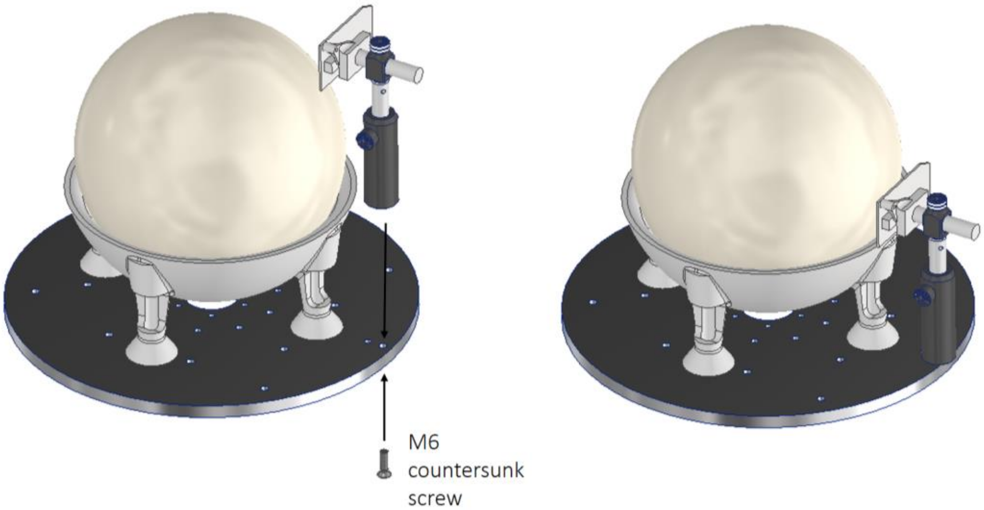


Figure 5: Optical sensor – platform assembly.

Fig5-Optical-Motion_Sensors.PNG

Connect the pins on the Arduino 5V, GND, and two digital pins.

Sensor characterization

The library needed to interface with the sensors is available on GitHub, this one was created by Martijn and modified by Zapmaker [8] we have added the access to the SQUAL register, which is gives the reading of how good is the surface pattern to detect xy displacements. On Figure 6 you can see the relationship of error in percentage and SQUAL value for a one revolution measurement being 120 the SQUAL maximum value and a value of 0 no detection of the surface.

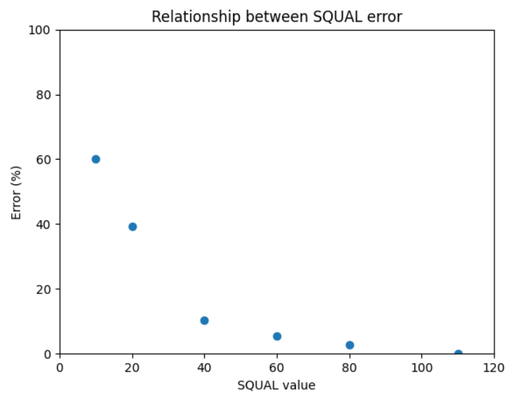


Figure 6: Relationship between error of the measurement and SQUAL value.

Fig6-Optical-Motion_Sensors.PNG

The characterization of the ADNS2610 optical sensors was performed collecting 30 revolutions using the different axes of the polystyrene sphere. The results obtained reflected the number of the optical sensor internal units per revolution which are 9.391 in average. The polystyrene sphere has a perimeter of 61.86 cm therefore, the number of sensor internal units per cm is equal to 151.81.

The SQUAL value was simultaneously recorded and the average value of it was 82.56 ± 23.92. The figure 14 (left) shows the SQUAL value distribution over the samples. The figure 14 (right) shows the relationship of the speed of rotation as the increment in mouse internal units between two samples and the SQUAL value.

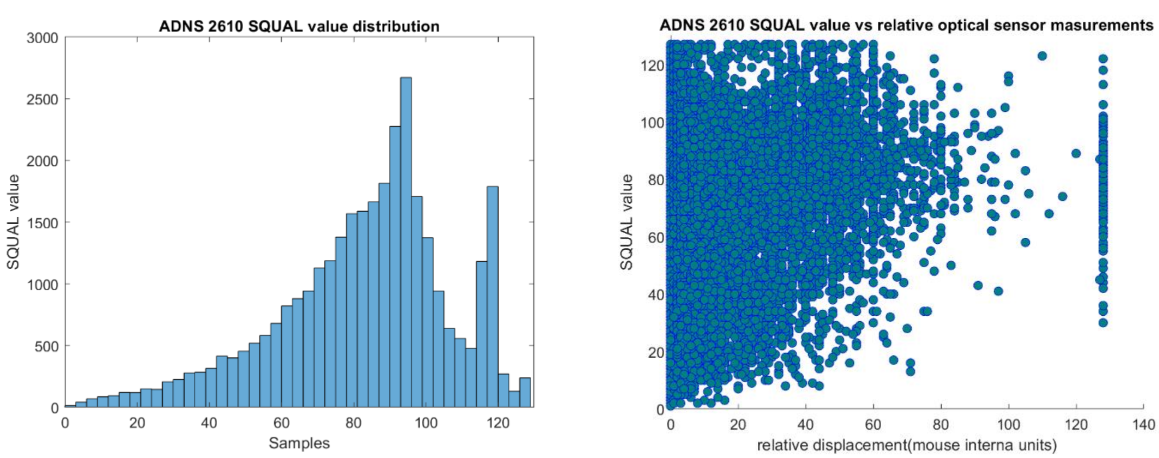


Figure 7: Distribution of the SQUAL value (left) and relationship between the speed and the SQUAL value.

Fig7a-Optical-Motion_Sensors.PNG

Fig7b-Optical-Motion_Sensors.PNG

Calibration

The calibration can be done adjusting the vertical position on the making coincident the equator of the sphere with the optical flow sensor. Then the horizontal position can be achieved by adjusting the horizontal micrometer until a SQUAL value of more than 100 has been achieved.

Embedded screens

The two 8” SKD819VAHT-9 TFT displays are attached with the rotary platform using two Thorlabs RS6P_M posts. The displays are attached to the posts with a 3D printed part (Screen attachment 1) and the display frame is composed by three laser cut acrylic parts and some laser cut spacers. Eight M4 screws and nuts are required to build the acrylic structure and an M6 is required to attach the 3D printed attachment with the Thorlabs® post.

Table 1: Bill of materials (For each screen).

Component	Quantity	Supplier	Reference
Screen 8" TFT LCD SKD with HDMI	1	-	SKD819VAHT-9
Screen holder front	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
Screen holder back	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
Screen holder back 2	1	Laser cut part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
Screen attachment 1	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
Spacer	4	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
Spacer 2	4	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Embedded%20 screens
RS6P_M	1	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=RS6P/M
M4 screw	8	RS Components	https://uk.rs-online.com/web/p/socket-screws/0281057/
M4 nut	8	RS Components	https://uk.rs-online.com/web/p/hex-nuts/0189579/
M6 screw	1	RS Components	https://uk.rs-online.com/web/p/socket-screws/8741030/
M3 screw	3	RS Components	https://uk.rs-online.com/web/p/machine-screws/0560625/
M3 nut	3	RS Components	https://uk.rs-online.com/web/p/hex-nuts/0527230/

Assembly instructions

In order to assembly the screen you just need attach the display with the front and back screen holders using spacers and M4 screws and nuts.

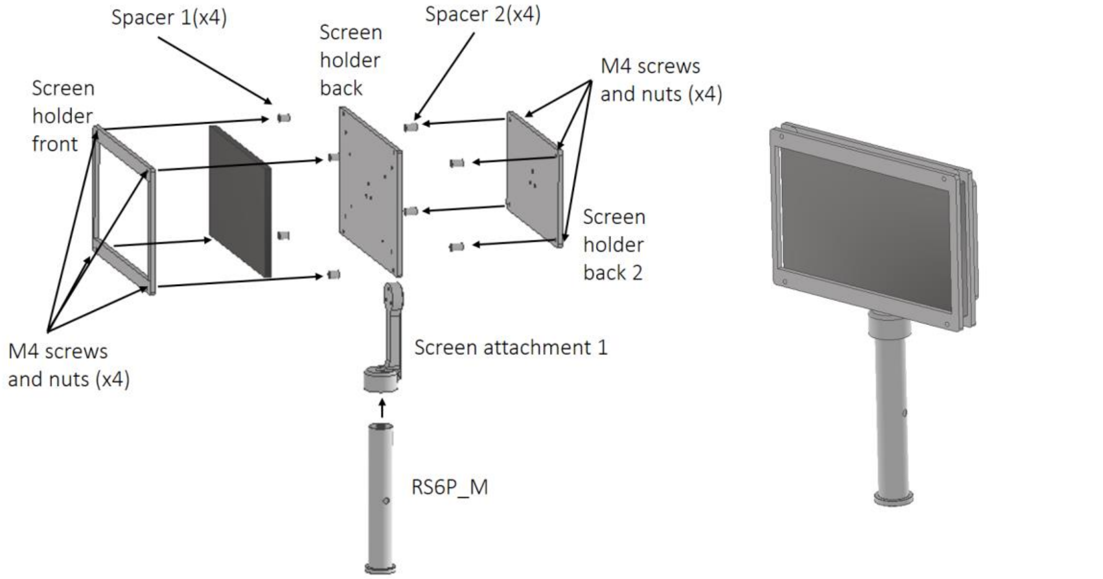


Figure 1: Screen assembly.

Fig1-Embedded-Screens.PNG

Separately assemble the 3D printed Screen attachment 1 with the Screen holder back as in Figure 2.

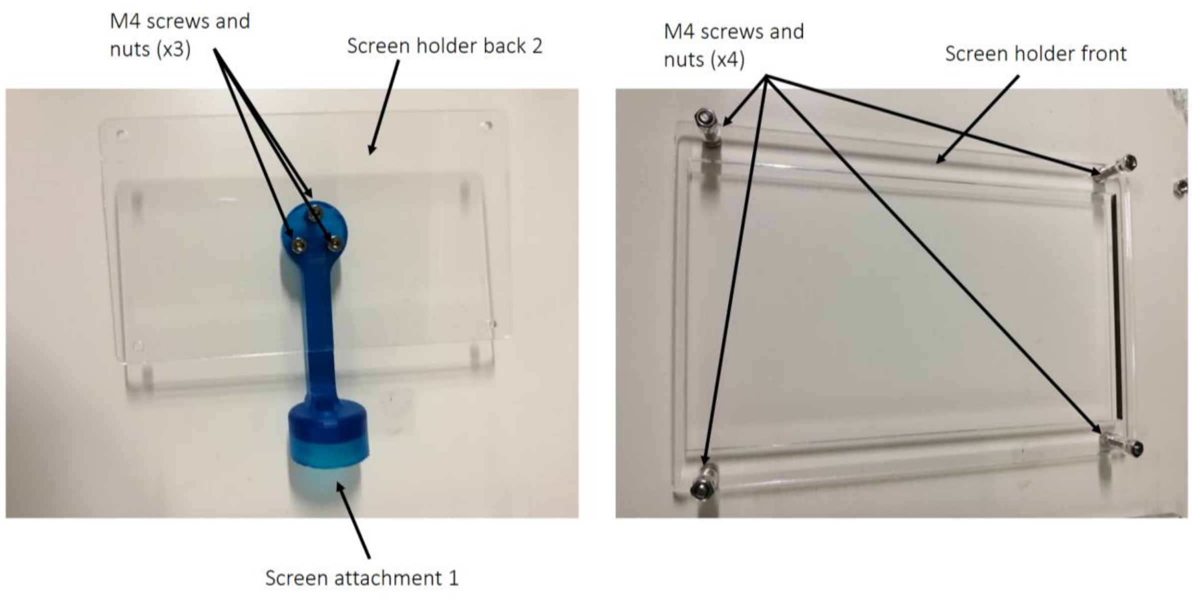


Figure 2: Front holder assembly.

Fig2-Embedded-Screens.PNG

Attach the electronic board with the screen holder back using 3 M3 screws and nuts (Figure 3). And then attach the two screen back holders with M4 screws.

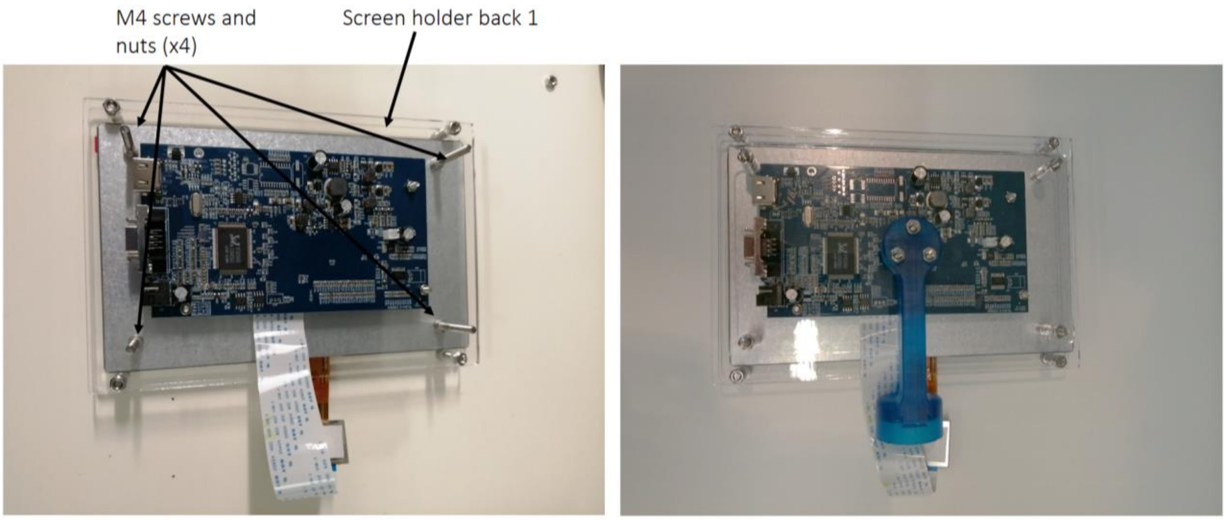


Figure 3: Back holder assembly.

Fig3-Embedded-Screens.PNG

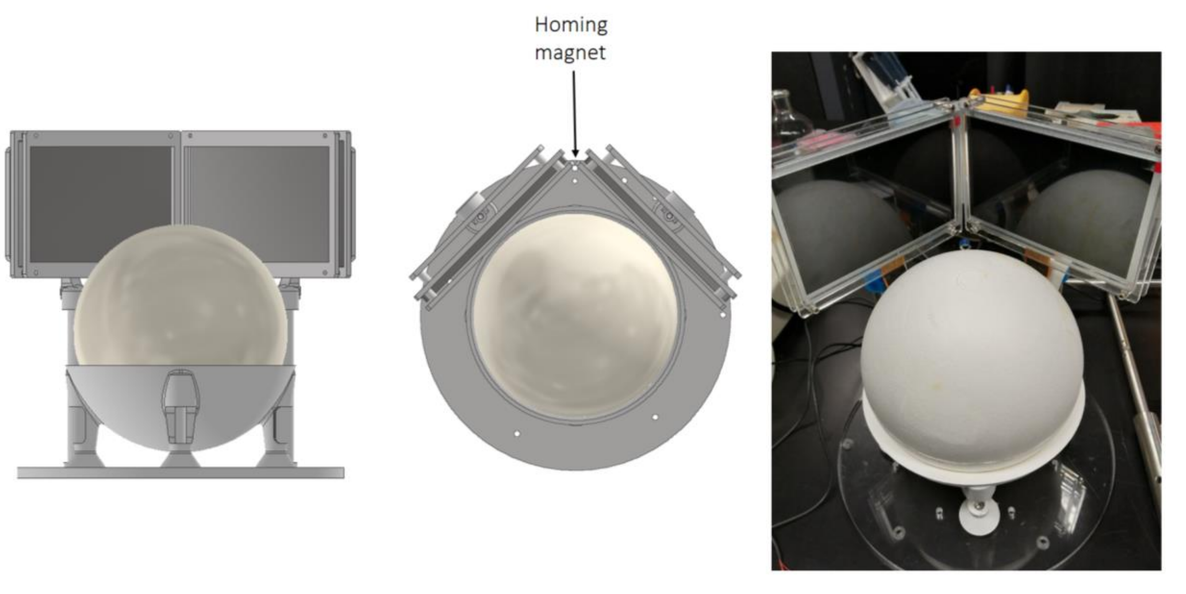


Figure 4: Location of the screens on the platform.

Fig4-Embedded-Screens.PNG

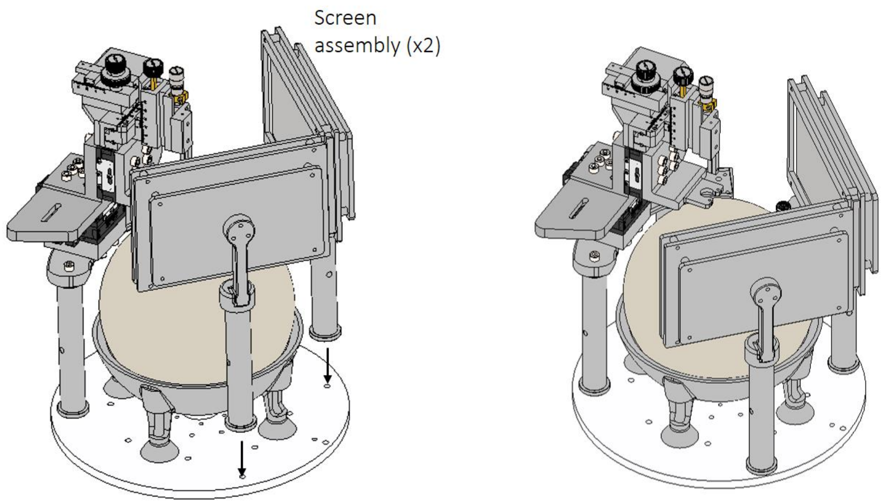


Figure 5: Head holding system and circular platform assembly.

Fig5-Embedded-Screens.PNG

Head holding system with electrophysiology probe micromanipulator

The head holding system has been designed to be used in imaging and electrophysiology experiments. This is the reason it has three axes of translation. The observation of neurons through the implanted cranial window on the head of the rodent while that one rotates require an independent system to align the axis of the motor rotation with the microscope field of view (Figure 1).

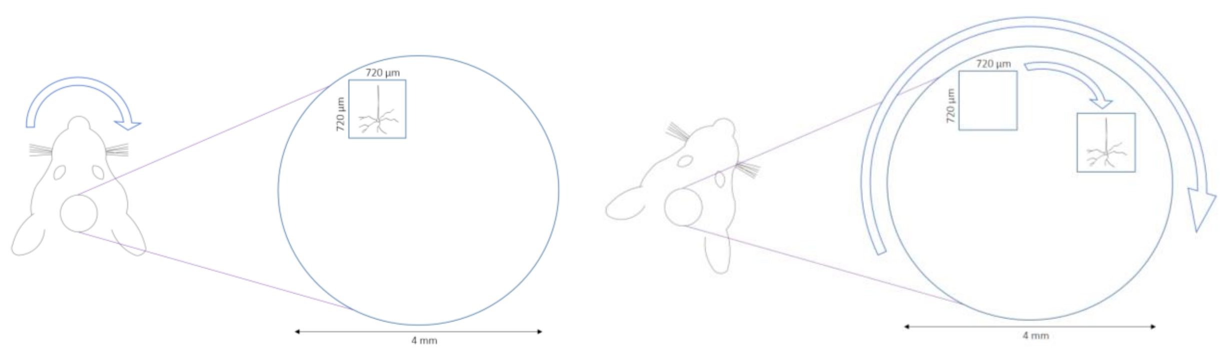


Figure 1: Displacement of the cells due to the animal's head rotation.

Fig1a-Head-Holding-System.PNG Fig1b-Head-Holding-System.PNG

For these reason a three degrees of freedom head fixation post has been designed to get the displacements on the plane (Figure 2) and the vertical displacement to adjust the height depending on the animal's size.

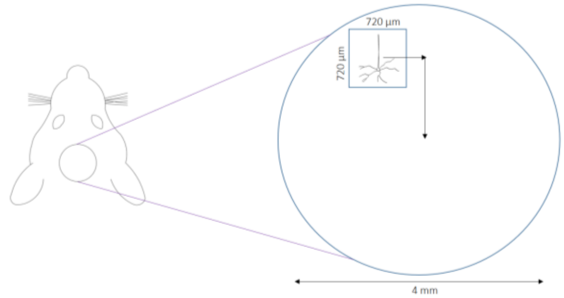


Figure 2: Readjustment of this center of rotation.

Fig2-Head-Holding-System.PNG

This head holding system is based on the assembly of 3 Thorlabs® translational stage MT1\M to get the three translational movements with reliability. The main goals of this design are: (1) Adjust the height from mouse to mouse, (2) Adjust the center of the microscope field of view with the center of rotation and (3) reliability and repeatability experiment after experiment. Also the MT405 side mounted actuator adapter. The resolution of the system is 10 microns, the smallest measure of the micrometers and the range of each micrometer is 13 mm.

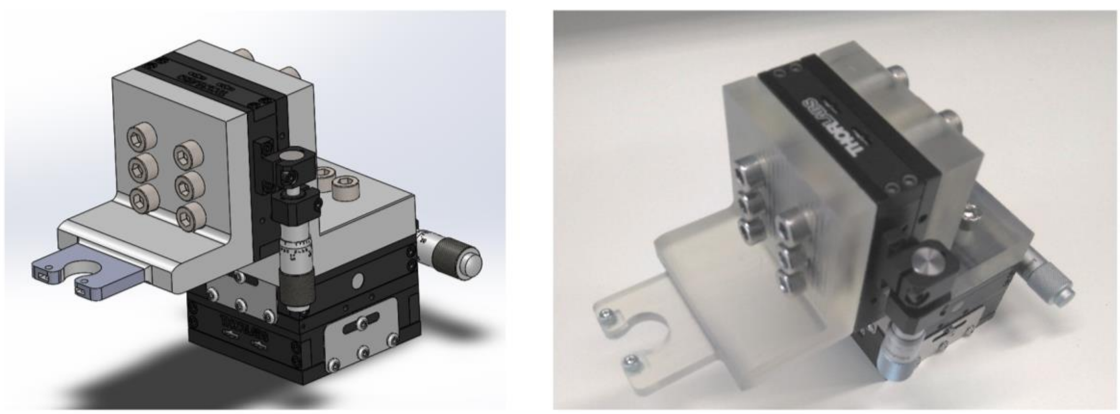


Figure 3: Virtual assembly of the head post designed using Solidworks ® software (left) and real assembly (right).

Fig3-Head-Holding-System.PNG

The materials needed for the assembly are: the 2 3D printable parts, the three MT1\M translational stages, three MT405 side mounted actuator adapter, two M2.5 Nuts, two hexagonal M2.5 screws, fifteen M6 screws two of them optional and two Bollhoff M6 threaded inserts (also optional).

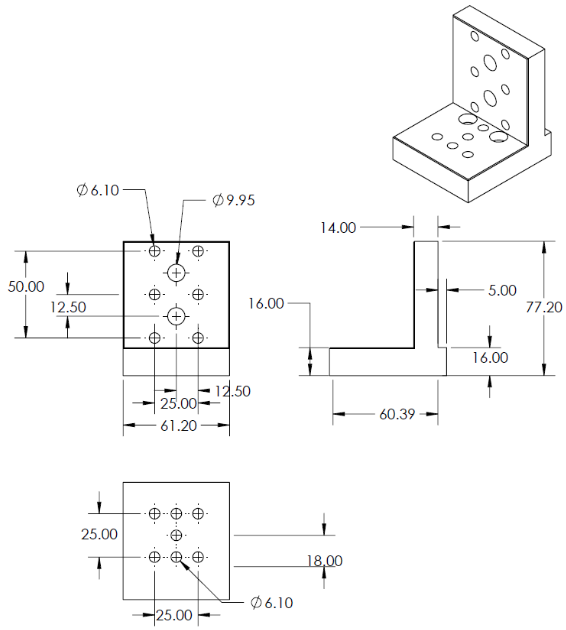


Figure 4: Drawings of the link 1:2 scale.

Fig4-Head-Holding-System.PNG

The 3D printed parts have been printed using a Form2 SLS 3D printer from Formlabs® [9] using the standard features with Clear V4 resin type.

Figure 5: Thorlabs® components needed: MT1\M translational stage (left) and MT405 side mounted actuator adapter (right).

Fig5-Head-Holding-System.PNG

Assembly instructions

From the initial design for imaging purposes mentioned before, we designed an additional head holder plate (Head plate) which is mechanically connected with three M3 screws to a Left handed micromanipulator MM33. This device provides fine adjustment (0.10 mm) of the three axes with a finer micrometer adjustment for the vertical stage ideal to precisely adjust the depth of the probe implant. The total range of motion is 10 mm for the x axis and 20 mm for the Y and Z axes.

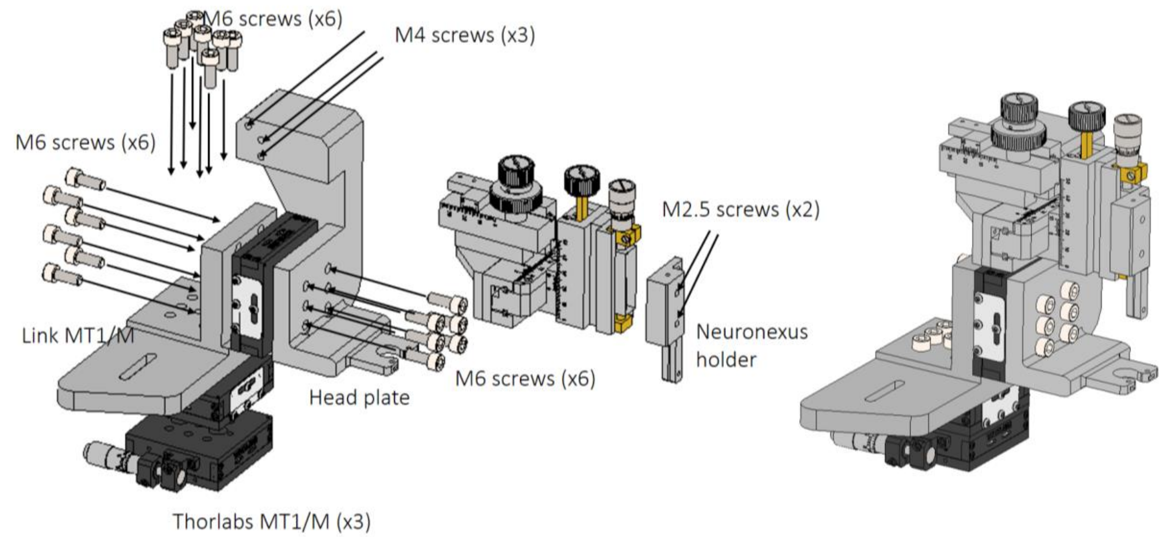


Figure 6: Head holding system assembly.

Fig6-Head-Holding-System.PNG

The parts have been successfully 3D printed using FormLabs Clear V4 resin. And the resulting stiffness has been proved enough for imaging and electrophysiology integrity experiments.

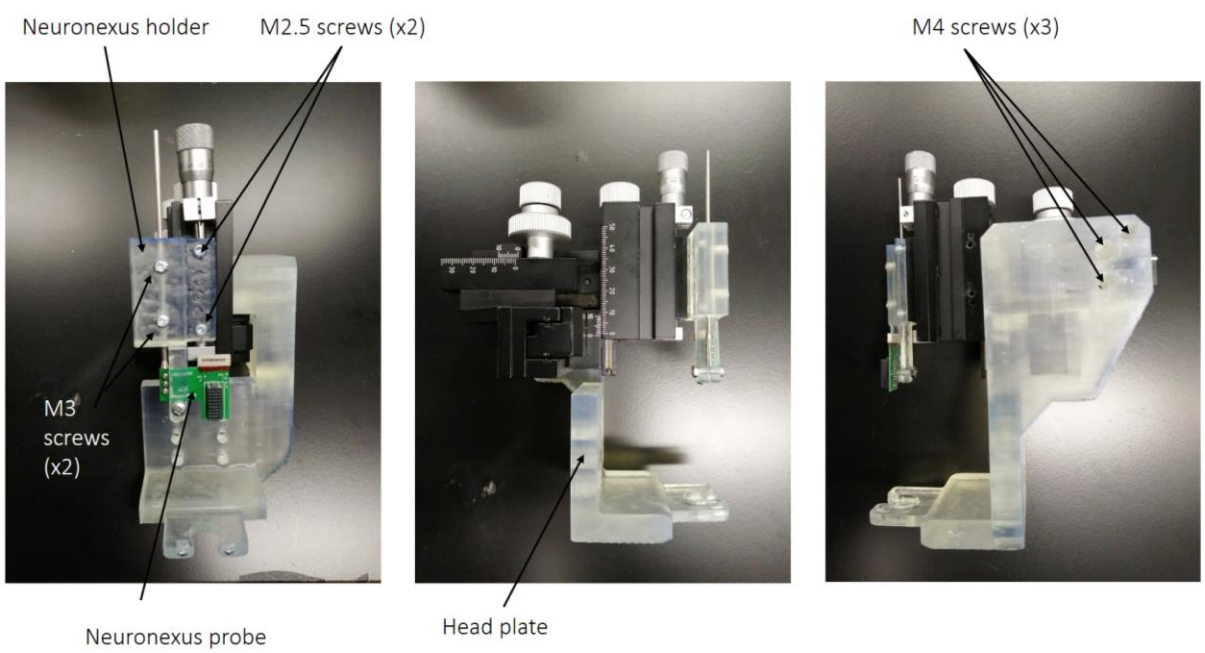


Figure 7: Head plate system sub-assembly.

Fig7-Head-Holding-System.PNG

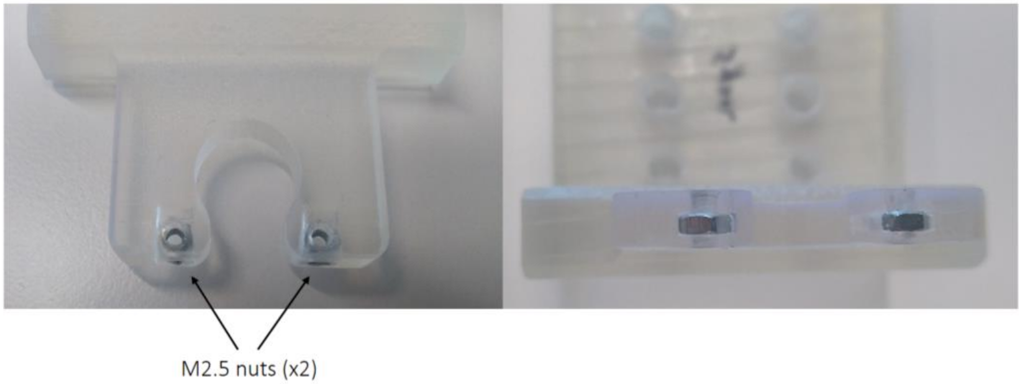


Figure 8: Head plate system nuts insertion.

Fig8-Head-Holding-System.PNG

Table: Bill of materials.

Part name	Manufacturer	Units	Reference
Link Link MT1/M	3D printed part	1	https://github.com/atranvan/vestibular_setup/tree/Files/Head%20fixation%20system
Head plate	3D printed part	1	https://github.com/atranvan/vestibular_setup/tree/Files/Head%20fixation%20system
Neuronexus holder	3D printed part	1	https://github.com/atranvan/vestibular_setup/tree/Files/Head%20fixation%20system
Left handed micromanipulator MM33	Sutter Instruments		https://www.sutter.com/MICROMANIPULATION/mm33.html
MT1/M translational stage	Thorlabs	3	MT1/M
MT405 side mounted actuator adapter	Thorlabs	3	MT405
M6 hex bold screws 16mm length	RS components	15 (2 optional)	281-144
M2.5 hex bold screws	RS components	4	483-8124
M2.5 nuts	RS components	2	
M6 threaded inserts	RS components	2 (optional)	664-7359
M4 screws	Thorlabs	3	https://www.thorlabs.com/thorproduct.cfm?partnumber=HW-KIT1/M

The Head holder is assembled on the the Ring with M6 screws, also 3D printed in clear V4 resin from FormLabs in a Form 2 3D printer. The Ring is assembled with two RS6P_M posts with the rotary stage platform.

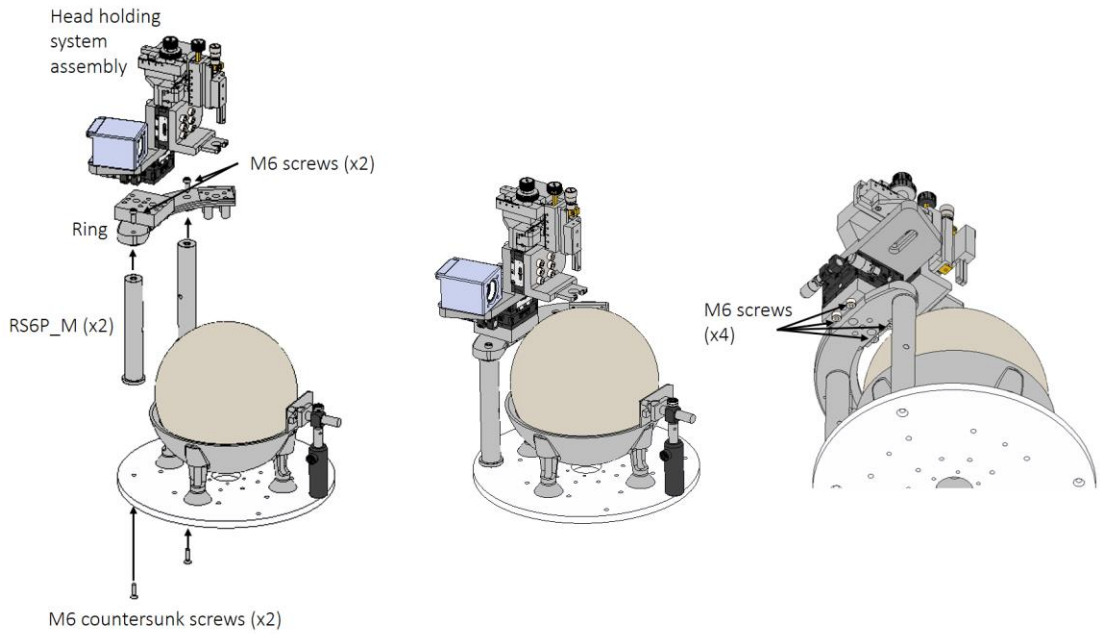


Figure 9: Head holding system and circular platform assembly.

Fig9-Head-Holding-System.PNG

Optic fiber holder for optogenetics

There is also the option to attach the Thorlabs FCM13/M with the MM33 micro manipulator by using a custom 3D printed holder. That enables the possibility to place the optogenetic light source in any position inscribed inside the cranial window area.

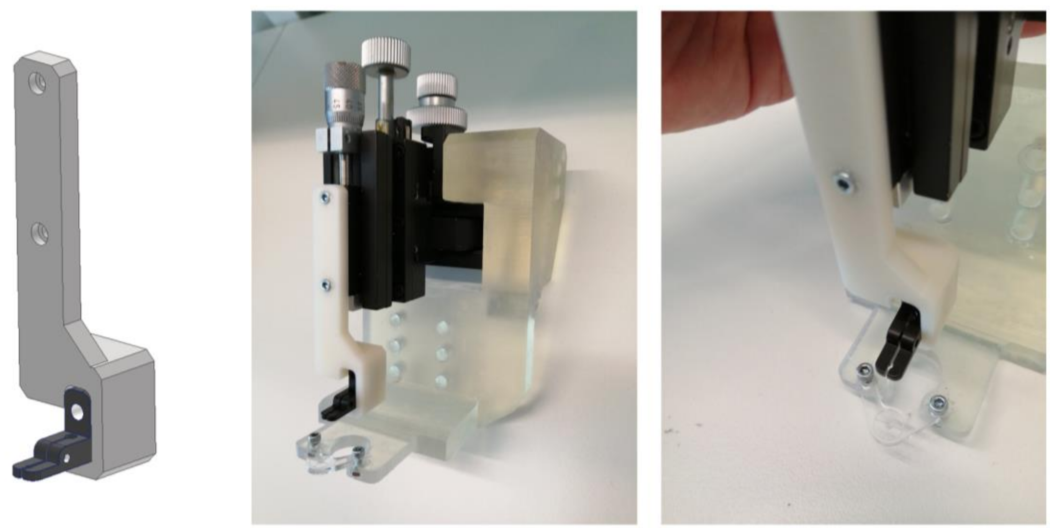


Figure 10: Optical fiber holder.

Fig10-Head-Holding-System.PNG

Head fixation clamp

This is the design of the chronical implanted clamp for experimentation with head fixed mice used with the previously described head holding device.

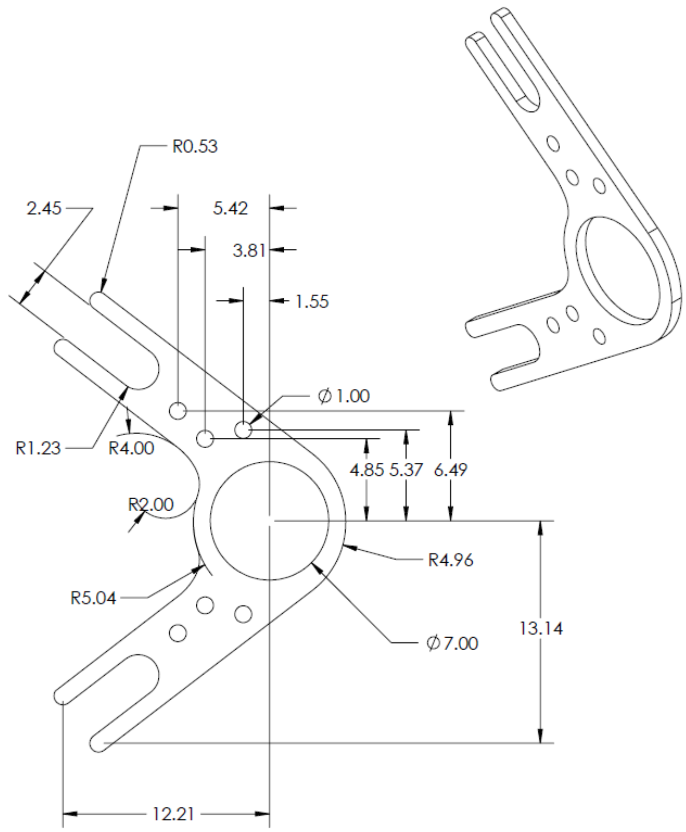


Figure 1: Head clamp drawings.

Fig1-Head-Clamp.PNG

The following study aims to assess if with the change from the current head clamp (1 mm thickness) to Titanium or Steel, reducing the thickness to 0.8 mm, the head plate performance also improves on stiffness. This would provide better stability for two-photon microscopy in awake animals. This comparison can be performed knowing that the materials will be manufactured using CNC technique from a block of homogeneous and isotropic material.

The three materials simulated on the Solidworks simulation tool have been:

- Aluminum 6061-T6 **1 mm** of thickness (0.3g).
- Titanium Grade 2 **0.8 mm** of thickness (0.41g).
- Stainless steel 316 **0.8 mm** of thickness (0.73g).

The Initial conditions for the simulation are:

– A static load applied to the center ring (Blue arrows on Figure 2).
– Three axis fixture on the parts where the metric 2.5 screws are placed (green arrows on Figure 2).

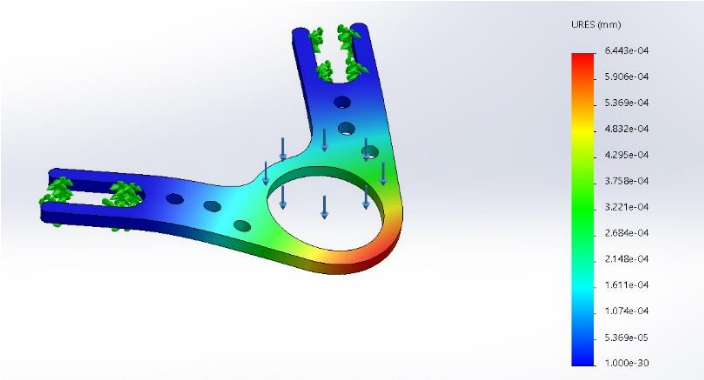


Figure 2: Graphical display of the simulation.

Fig2-Head-Clamp.PNG

The results of maximum displacements obtained for each condition

– Aluminum max. displacement = 9.445e-04 mm
– Titanium max. displacement = 11.79e-04 mm
– Stainless Steel max. displacement = 6.443e-04 mm

In conclusion, with the stainless steel head plate of 0.8 mm thickness, the displacement and strain of the head clamp is less than the Aluminum one (1 mm). Otherwise with the Titanium we lose stiffness with 0.8 mm thickness.

Finally, the manufacturing supplier was 3D hubs and the chosen material:

CNC machining / Stainless steel 316L / Smoothed (Ra 1.6µm, 63µin)

The manufacturing files are available on:
https://github.com/atranvan/vestibular_setup/tree/Files/Head%20calmp/Manufacturing%20files

Pupil tracking camera-mirror complex

Additionally, it is possible to add a camera on the head holder. The ELP webcam camera 1080P 30fp [10] along with a Thorlabs FEL0750 - Ø1" Long pass Filter, Cut-On Wavelength: 750 nm [11] mounted on a CP35/M - 30 mm Cage Plate [12] with a SM1L03 - SM1 Lens Tube [13]. The image acquired of the animal's pupil is reflected from the FM02R - 25 mm x 36 mm Red Hot Mirror, AOI: 45° [14]. The mirror can be adjusted with Thorlabs Posts elements and the camera can be rotated and translated for its adequate positioning.

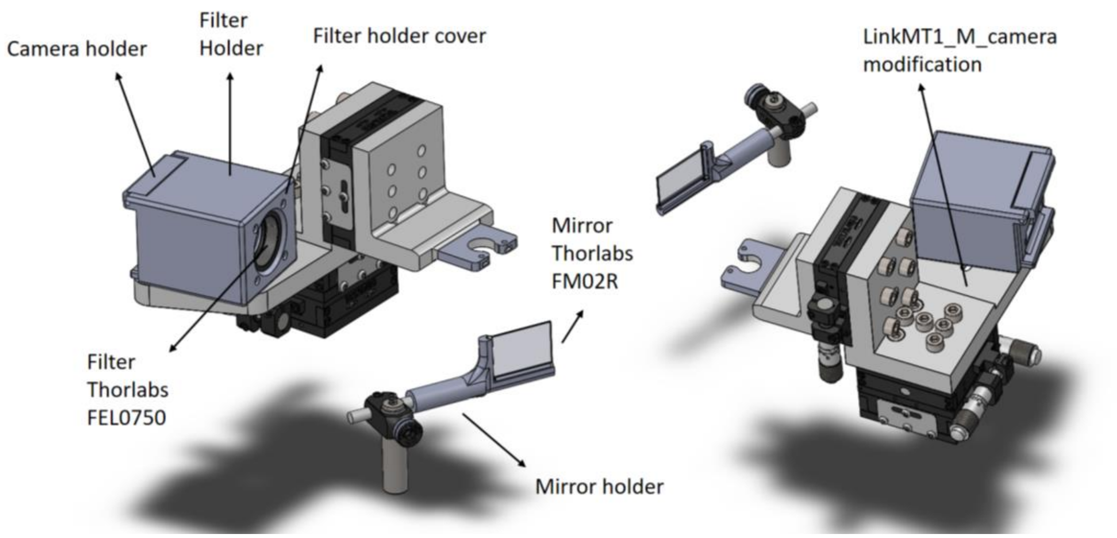


Figure 1: Second configuration description.

Fig1-Camera-Mirror.PNG

Bill of materials

Component	**Quantity**	**Supplier**	**Reference**
Mirror holder	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Camera%20Mirror%20complex
Camera holder	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Camera%20Mirror%20complex
Filter holder	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Camera%20Mirror%20complex
Filter holder cover	1	3D printed part	https://github.com/atranvan/vestibular_setup/tree/Files/Camera%20Mirror%20complex
M2 screw	4	-	-
M3 screw	6	-	-
M2 nuts	4	-	-
M6 screw	1	-	-
M6 nut	1	-	-
FEL0750 - Ø1" Long pass Filter	1	Thorlabs	https://www.thorlabs.de/thorproduct.cfm?partnumber=FEL0750
CP35/M - 30 mm Cage Plate	1	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=CP35/M
SM1L03 - SM1 Lens Tube	1	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=SM1L03
FM02R - 25 mm x 36 mm Red Hot Mirror	1	Thorlabs	https://www.thorlabs.com/thorproduct.cfm?partnumber=FM02R
ELP webcam camera 1080P 30fp	1	Amazon	https://www.amazon.co.uk/gp/product/B015PCAVZG/ref=ppx_yo_dt_b_search_asin_title?ie=UTF8&psc=1

Assembly instructions

- Cut 2 parts of silicone tube with the same distances as the mirror sides: 36 mm and 25 mm.
- Glue both parts with the mirror holder.
- Use a scalper to meake a longitudinal cut along both blued tubes.
- Insert a 6 mm diameter Thorlabs post.

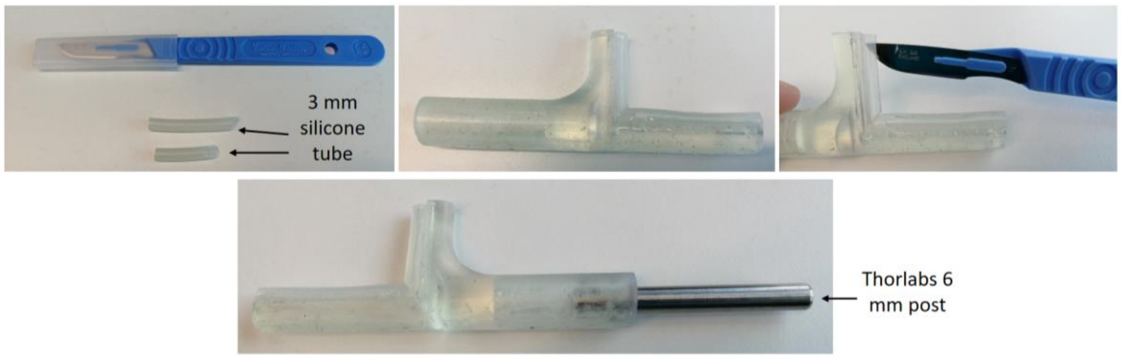


Figure 2: Mirror holder assembly.

Fig2-Camera-Mirror.PNG

- Use a 3D printing material with opaque features (FormLabs black resin) if the resin is clear, use black matt spray to paint it.
- Use four M2 screws and nuts to attach the camera with the camera holder part.
- Insert the Long Pass Filter, mounted on a CP35/M and a SM1L03 - SM1 Lens Tube in the filter holder and use four M3 screws to attach them with the filter holder cover.
- Use two long (25-30 mm) M3 screws as a shafts to open and close the filter holder.

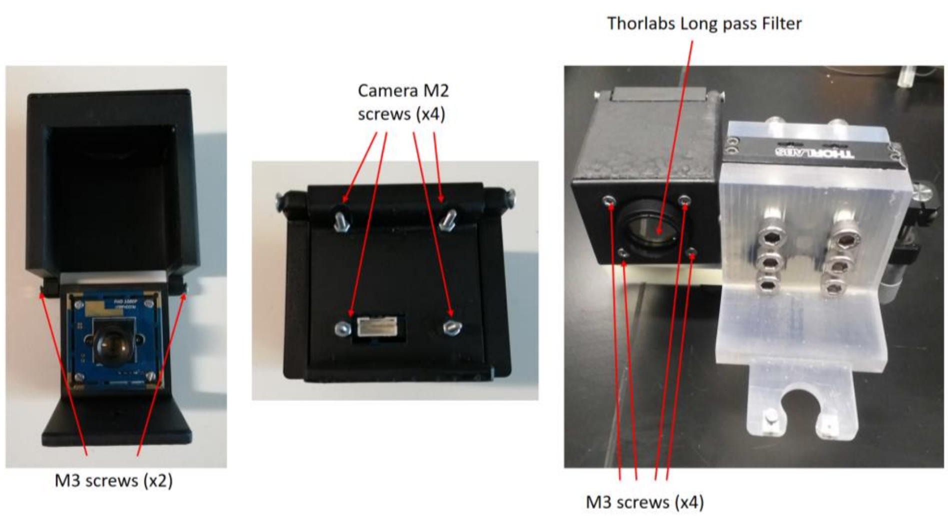


Figure 3: Camera holder assembly.

Fig3-Camera-Mirror.PNG

– Use a M6 screw and nut to attach the camera holder with the LinkMT1_camera_modification.

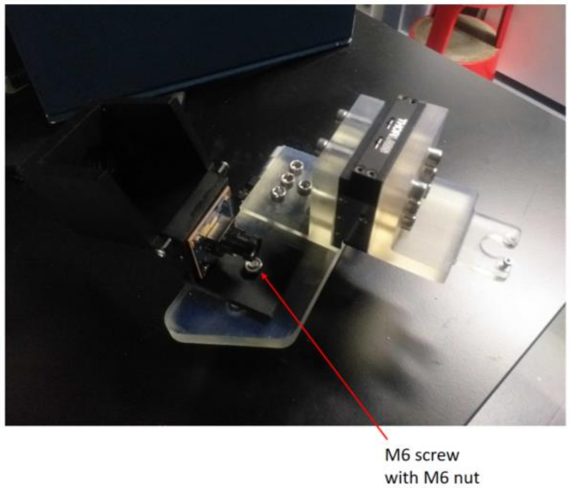


Figure 4: Head fixation system assembly.

Fig4-Camera-Mirror.PNG

– Attach the mirror holder on the setup using Thorlabs components (RA90TR/M [15] and 12.7 mm post [16]).
– Assembly the head fixation system with the left ring.

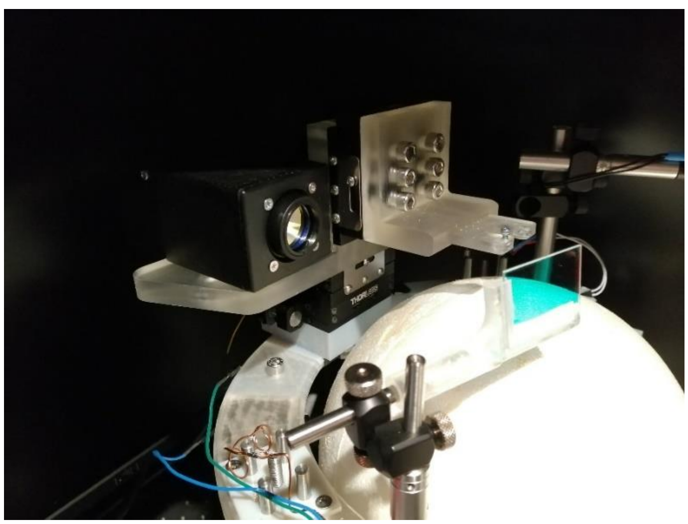


Figure 5: Modifications assembled on the real setup.

Fig5-Camera-Mirror.PNG

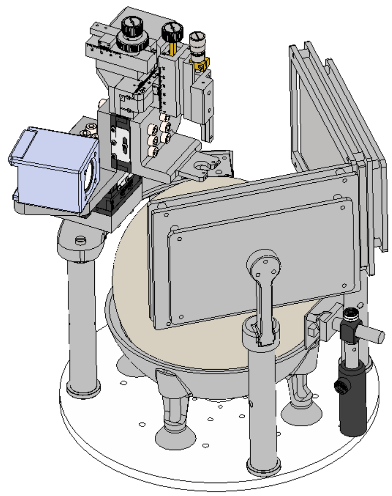


Figure 6: Camera asembled on the platform with the rest of the components.

Fig6-Camera-Mirror.PNG

Characterization and validation

The rotary stage accuracy and repeatability have been evaluated by recording the angle (°) of the incremental encoder (2400 pulses per revolution) and the angle obtained from the teensystep step counter simultaneously. Figure 1 shows one of many tests made to evaluate the stage performance, in this case without the load of the head holder.The stage is repeatly sent to the set point positions (0 and 360 degrees).. The results obtained are 360.06 ± 0.11° and 0.04 ± 0.07 °. In figure 1

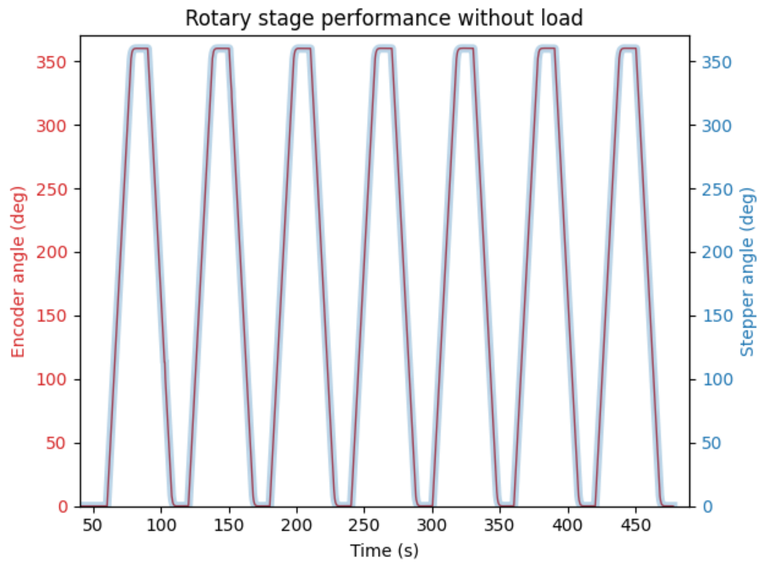


Figure 1: Rotary stage performance.

Fig1-Caracterization.PNG

Minimum incremental motion (MIM) and backlash

The Minimum incremental motion reliably measured corresponds to 0.1 degrees. The backlash observed in the worst case scenario corresponding to the offset created on the change in direction of the MIM test has been 0.04 degrees.

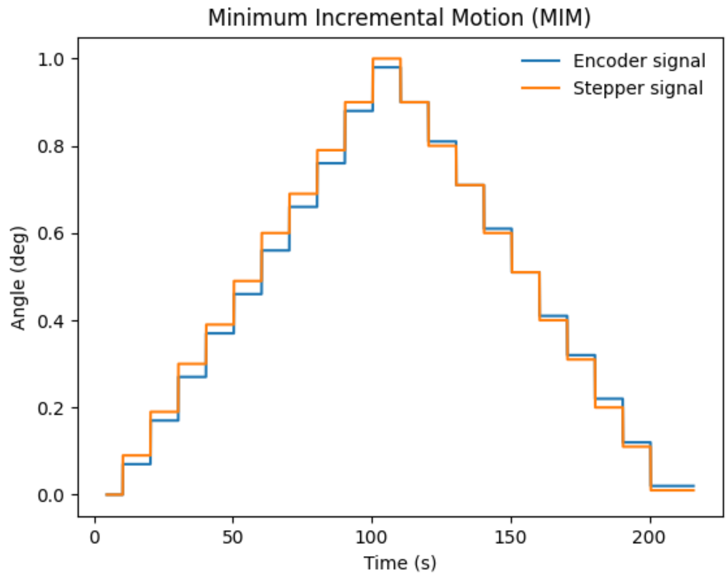


Figure 2: Minimum incremental motion.

Fig2-Caracterization.PNG

Accuracy and repeatability

In order to evaluate the accuracy and repeatability of the rotary stage, a sequence of increments of 45 degrees in both rotation directions has been performed, collecting 8 position deviations in each direction (16 per each velocity/acceleration condition). The overall accuracy and repeatability have been calculated from all conditions according to the following equations (https://www.newport.com/n/motion-basics-terminology-and-standards).

Accuracy:

$$P = \left|max_j(\bar{\bar{x}}_j) - min_j(\bar{\bar{x}}_j)\right| = \left|max_j\left(\frac{\bar{x}_{i\uparrow} + \bar{x}_{i\downarrow}}{2}\right) - min_j\left(\frac{\bar{x}_{i\uparrow} + \bar{x}_{i\downarrow}}{2}\right)\right|$$

Repeatability

$$R = 3\frac{1}{8}\sum_{i=1}^{8}\left(\frac{s_{i\uparrow} + s_{i\downarrow}}{2}\right)$$

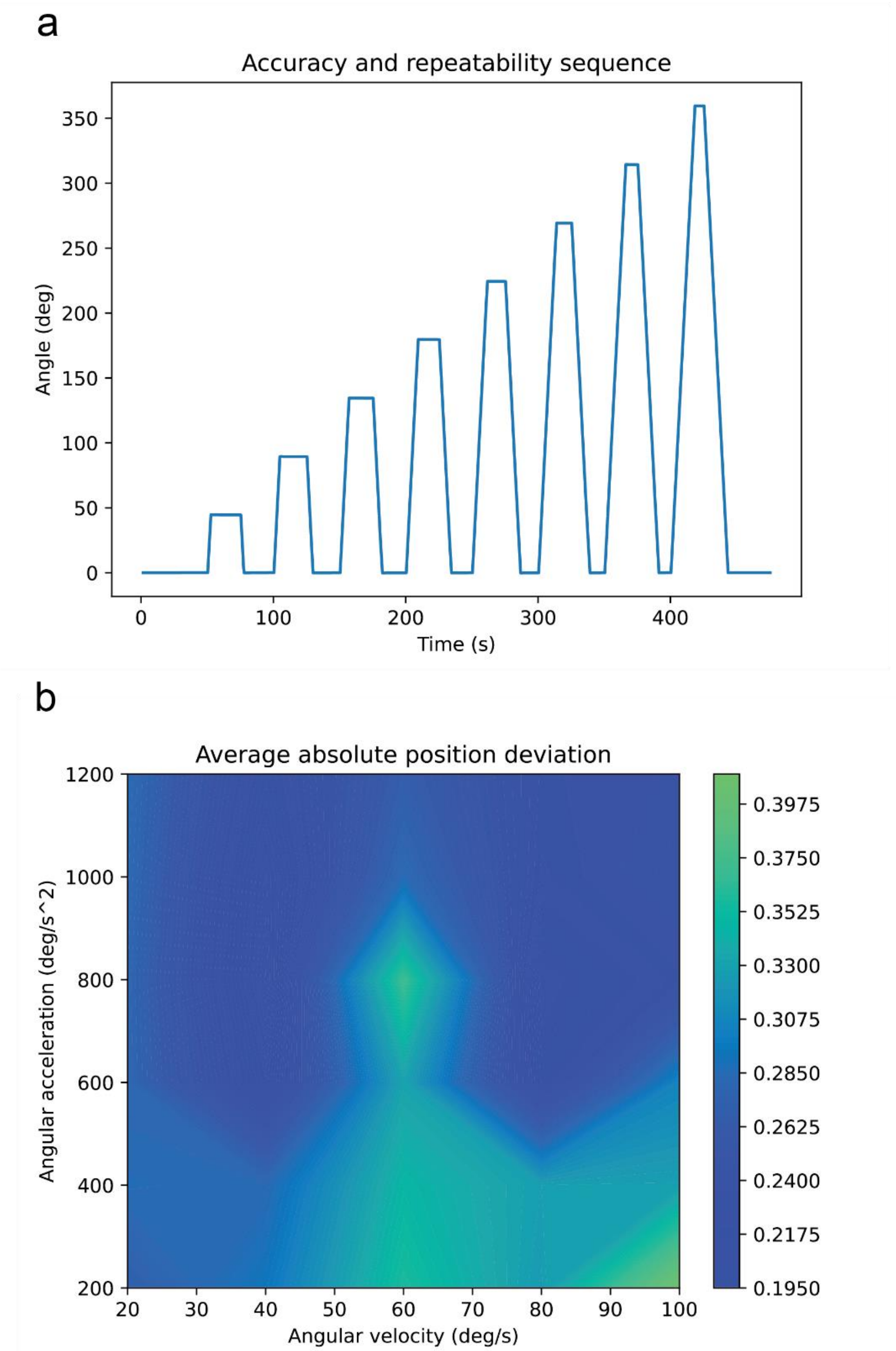


Figure 3: Accuracy and repeatability test sequence (a) and average of absolute position deviation in every angular velocity and acceleration condition (b).

Fig3-Caracterization.PNG

Closed loop characterization

For the closed loop algorithm, the stability of the system response has been evaluated by the analysis of the step response for all previously described conditions (20-100 $°\cdot s^{-1}$ and 200-1200 $°\cdot s^{-2}$). From that a contour plot has been extracted to be used as a map to avoid regions of inaccuracy and instability. Sometimes event achieving a small error the stage can overshoot as shown in figure 4b. On figures c and d are shown the regions to avoid errors and instabilities around the set point.

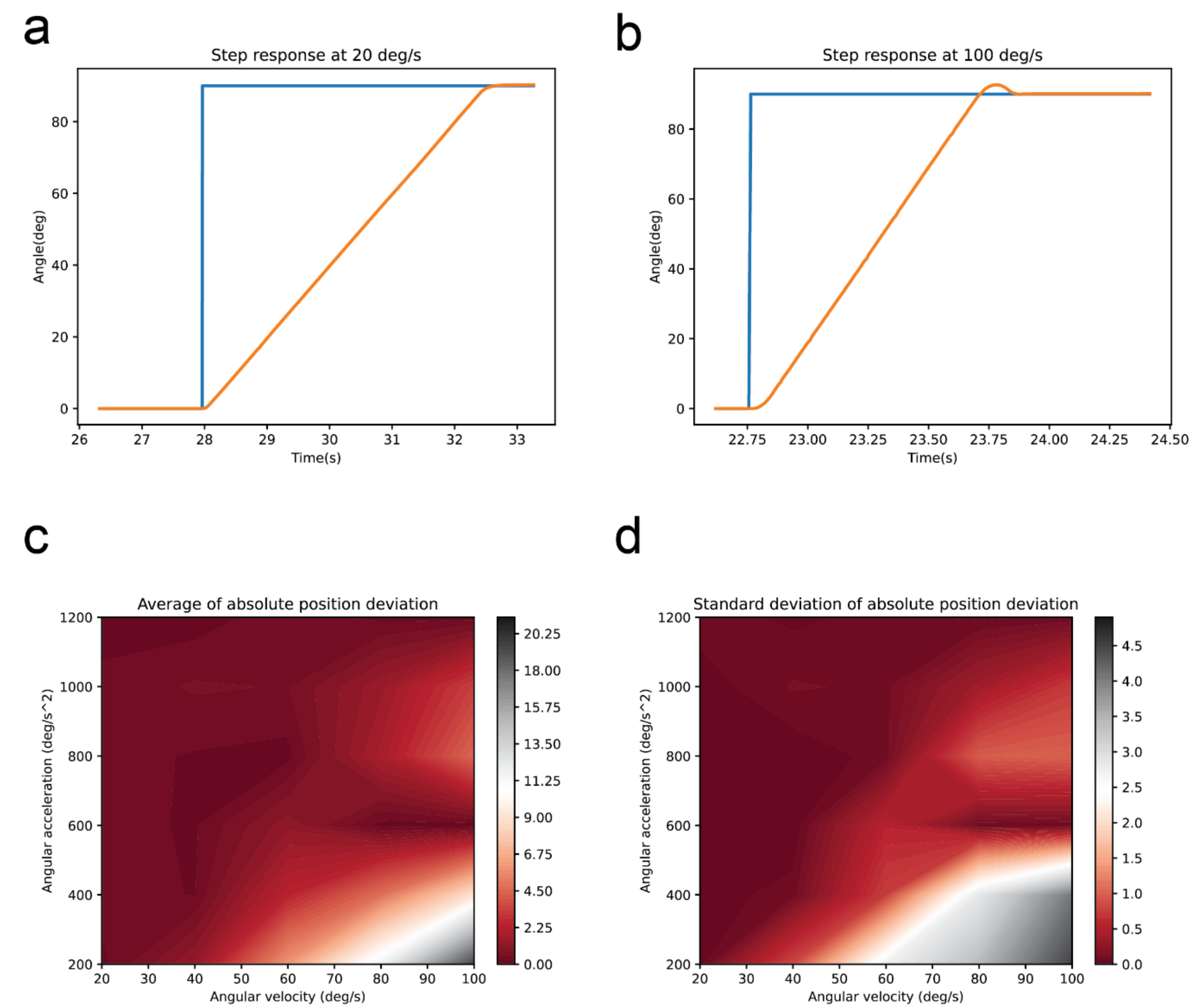


Figure 4: Step functions at 20 $°\cdot s^{-1}$ /200 $°\cdot s^{-2}$ and 100 $°\cdot s^{-1}$ /1200 $°\cdot s^{-2}$ (Figures a and b respectively). Accuracy and repeatability test sequence (c) and average of absolute position deviation in every angular velocity and acceleration condition averaged over several attempts to reach the position imposed by a step function (d).

Fig4-Caracterization.PNG

Specifications of the rotary stage

Resolution stepper motor (°)	0.0024

Resolution Encoder (°)	0.024
Accuracy (°)	0.37
Repeatability (°)	0.10
Minimum incremental motion (°)	0.1
Maximum angular velocity ($°\cdot s^{-1}$)	100
Maximum angular acceleration ($°\cdot s^{-2}$)	1200
Backlash (°)	0.04

Required libraries and software packages

Software packages

- Arduino IDE: https://www.arduino.cc/en/software
- Teensyduino: https://www.pjrc.com/teensy/teensyduino.html

Libraries

Basic

- Optical sensors ADNS 2160: https://github.com/zapmaker/OptiMouse
- Stepper motor control: https://luni64.github.io/TeensyStep/
- Encoder: https://github.com/PaulStoffregen/Encoder

Future implementations

These are Optical motion sensor options with higher capabilities than the ADNS 2160. All of them use the SPI bus.

- Optical sensors ADNS 3500: https://github.com/Tom101222/Adns-3050-Optical-Sensor
- Optical sensors PWM3360: https://github.com/mrjohnk/PMW3360DM-T2QU
- Optical sensors ADNS 9800: https://github.com/mrjohnk/ADNS-9800

Basic Arduino code description

The different Arduino sketches are available on: https://github.com/atranvan/vestibular_setup/tree/Files/Arduino%20code

Closed_loop.ino

The closed loop code uses the measured angle increment as a setpoint for the proportional control. The animal can control the rotation of the platform.

Open_loop.ino

The Open loop example uses two variables introduced by the user (eg. 0-360 degrees) as a set points to switch every certain interval and therefore to swing from one to the other.

Open_loop_SD.ino

This example is like the open loop example but saving the different variables on the SD card on the Teensy 3.5 SD card slot. That program was used to record accuracy and repeatability data of the stage.

Open_loop_moveAsync.ino

This example is like the Open_loop_SD.ino but instead of using the proportional control it only bases its rotation movement on the teensystep method moveAsync() which is a non-blocking trapezoidal profile movement.

Troubleshooting

Do you hear a friction noise?

Probably is the rotary joint spacer making contact with the slipring/rotary joint. One solution is to slide the Thorlabs posts to create a space between the two.

The platform does not mimic sphere rotation in the closed loop program and makes random movements or just spins indefinitely?

That might be caused for a bad connection of the wires of the sensor, check the connections on the control board (screw connectors) make sure they are coincident with the pinout proposed on the schematic. Check the soldering on the optical sensor board.

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