Open-source five degree of freedom motion platform for investigating fish-robot interaction

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A R T I C L E   I N F O

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A B S T R A C T

This paper presents the design, construction, operation, and validation of a robotic gantry platform specifically designed for studying fish-robot interaction. The platform has five degrees of freedom to manipulate the three-dimensional position, yaw angle, and the pitch of a lure. Additionally, it has a four-conductor slip ring that allows power and data to be transmitted to the lure for the operation of fins and other actuators that increase realism or act as stimuli to focal fish during an ethorobotic experiment. The design is open-source, low-cost, and includes purpose-built electronics, software, and hardware to make it extensible and customizable for a number of applications with varying requirements. © 2020 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Specifications table:

| Hardware name   | XYZψθ Fish |
|-----------------|-------------|
| Subject area    | Ethorobotics |
| Hardware type   | Mechatronics |
| Open source license | GPL-3.0 |
| Cost of hardware | 1550 USD |
| Source file repository | https://osf.io/yz6x7 |

1. Hardware in context

The concept of “biomimicry” refers to the idea that biological systems tuned for millenia by evolution can provide valuable design guidance to engineers who may be looking to solve problems similar to those that nature has already “solved” for various organisms. Biomimicry has been especially fruitful in robotics, offering roboticists opportunities to increase the efficiency and agility of mobile robots by drawing upon the locomotive strategies of animals [1]. This has been prevalent in underwater robotics, where a substantial body of work has developed to design robots that swim like fish (see a comprehensive review in [2]). Researchers have focused on many facets of fish-like robot design, from modeling fish-like locomotion [3,4] to designing bio-inspired and biomimetic robot bodies and actuators [5–10]. In general, fish-like robots may have advantages over propeller-driven underwater vehicles in dense environments with kelp or other materials that could clog...
a propeller, but they may also have advantages in applications where the goal is to observe fish without disturbing them by introducing a strange-looking robotic submarine into their midst [11]. For the latter subset of applications, one wonders how realistic a fish might have to be to avoid disturbing the focal subjects in its appearance, locomotion, and overall behavior. Further, if the goal of a robot is not just to “observe” fish without disruption, but to actually interact with fish socially, it becomes even less clear what design requirements or thresholds for realism might exist.

In recent years, the study of “ethorobotics” has become increasingly popular, with scientists and engineers alike asking questions about the nature of interactions between human-made and biological systems. Here, “ethorobotics” refers to the study of robots specifically designed to interact with biological organisms. Focusing on human-robot interactions specifically, Miklósi et al. [12] implored researchers to re-think the traditional “Uncanny Valley” [13] hypothesis. They write that the key to successful human-robot partnerships is in “social competence” and purpose-specific embodiment rather than imperfect approximation of human behavior. Ethorobotics is a relatively nascent field, but part of what those who study interactions between robotic and biological organisms hope to discover is just what “social competence” might mean, and a growing number of studies seek to interrogate this question using non-human animals.

While some work has been done in studying interactions between robots and land or amphibious animals, e.g. squirrels [14,15], guinea fowl [16], frogs [17], lizards [18,19], and others, fish have become a staple for studying what factors might be responsible for successful social interaction between robots and biological organisms. For example, several studies have looked at the effects of robot tail-beat frequency and other factors on interactions between fish facsimiles and Zebrafish [20–24], Golden Shiners [25,26], Mackerel [27], and Elephantfish [28]. While some of this work has been conducted with free-swimming lures [29,23,30], many of these studies have involved lures that are stationary or affixed to mobile robotic platforms (see Table 1), allowing for independent manipulation of factors like the fish’s relative velocity to a stream of water or its tail-beat frequency. This is key, especially because using a free-swimming fish, whose propulsion dynamics are only a Table 1

| Species         | Lure Support Approach and Motion Degrees of Freedom | Open Source | Citation, Year |
|-----------------|---------------------------------------------------|-------------|----------------|
| **Fixed Lures** |                                                   |             |                |
| Zebrafish       | A/B                                               | Abaid et al. [20], 2012 |
| Zebrafish       | X Y                                                | Polverino et al. [21], 2012 |
| Golden Shiners  | X Y                                                | Marras and Porfiri [26], 2012 |
| Golden Shiners  | X Y                                                | Polverino et al. [25], 2013 |
| Zebrafish       | X Y                                                | Polverino and Porfiri [22], 2013 |
| Zebrafish       | X Y                                                | Spinello et al. [53], 2013 |
| Mosquitofish    | X                                                   | Polverino and Porfiri [54], 2013 |
| Red Tiger Oscar | X                                                   | Ladu et al. [55], 2015 |
| Fighting Fish   | X                                                   | Romano et al. [41], 2017 |
| Fighting Fish   | X                                                   | Romano et al. [56], 2019 |
| **Single Axis and Fixed Trajectory Lures** |                                                   |             |                |
| Zebrafish       | A*                                                 | Ladu et al. [47], 2015 |
| Mackerel        | X                                                   | Kruusmaa et al. [27], 2016 |
| Elephantfish    | X                                                   | Donati et al. [28], 2016 |
| Red Tiger Oscar | X                                                   | Porfiri [24], 2018 |
| Archer Fish     | X                                                   | Coulson et al. [49], 2018 |
| Guppies, Tadpoles | B                                                   | Romano et al. [57], 2020 |
| **Mobile Lures**|                                                   |             |                |
| Stickleback     | B                                                   | Faria et al. [58], 2010 |
| Koi             | B                                                   | Swain et al. [59], 2012 |
| Zebrafish       | B                                                   | Bonnet et al. [42], 2012 |
| Killifish       | A                                                 | Phamduy et al. [50], 2014 |
| Zebrafish       | A                                                 | Butail et al. [51], 2014 |
| Guppies         | B                                                   | Landgraf et al. [60], 2014 |
| Zebrafish       | B                                                   | Bonnet et al. [43], 2014 |
| Zebrafish       | A                                                   | Ruberto et al. [48], 2016 |
| Zebrafish       | A                                                   | Bartolini et al. [52], 2016 |
| Guppies         | B                                                   | Landgraf et al. [61], 2016 |
| Zebrasfish      | B                                                   | Bonnet et al. [44], 2017 |
| Zebrafish       | A                                                   | Kim et al. [34], 2018 |
| Zebrafish       | B                                                   | Cazenille et al. [35], 2018 |
| Cave Molly      | B                                                   | Bierbach et al. [62], 2018 |
| Zebrafish       | A                                                   | Porfiri [24], 2018 |
| Zebrafish       | B                                                   | Cazenille et al. [36], 2018 |
| Zebrasfish      | B                                                   | Porfiri et al. [63], 2019 |
| Largemouth Bass | B                                                   | Polverino et al. [64], 2019 |
| Zebrafish       | B                                                   | De Lellis et al. [65], 2019 |
| Archer Fish     | A                                                   | Current Study |
Modeling the gross motion of fish, rather than the specific tail and body movements that propel them, has also received some attention in the literature [31–33]. Furthermore, researchers are beginning to investigate whether the gross motion of a fish and the gross motion of a robot are important for social interaction. For instance, the effects of “closed-loop” interactions between fish and robots have received some attention [34–36], and this approach shows promise for allowing scientists to investigate how different levels of “social competence” as defined by Miklósi et al. [12] might influence a fish’s reactions to and interactions with a robot. For a comprehensive reviews of recent work in animal-robot interaction, see Romano et al. [37], Mitri et al. [38], Krause et al. [39], and Webb [40].

In studies that address closed-loop interactions between fish and robots, e.g. Kim et al. [34] and Cazenille et al. [35], a robotic gantry is often used to move a fish facsimile (or “lure”) through a tank. These systems move the robot’s end-effector (the lure) in response to movements of live fish. The lure can therefore approximate social behaviors such as schooling. The robotic platform described in Kim et al. [34] consisted of a gantry situated above the tank that provided control of the lure’s three-dimensional position and yaw angle, but its design was not described sufficiently to allow other research groups to replicate the experiments without substantial reverse engineering. Additionally, this design does not allow for information or power to be transmitted to the lure as it moves, which limits the platform’s utility for investigating the combined effects of factors like tail fin beat frequency, tail fin actuation approach, other fin motion, or other functionalities of the lure. Examples of additional functionalities include the Fighting Fish lure of [41], which featured embedded LEDs to change its appearance, and the Elephantfish lure of [28], which included electrodes to produce electric fields. The platform used in Cazenille et al. [35], possibly the most sophisticated of the fish robot platforms used in ethorobotic studies, is described in three sequential publications [42–44]. While the design enables control of the planar position and yaw angle of multiple lures and is described in detail, it does not appear to be open source. The robot uses a mobile base situated underneath the tank, and the fish lure includes a magnetic base which is moved by the gantry without physical contact between the fish and the mobile base itself. This configuration has advantages in that the fish cannot see the motion of the gantry platform and that the gantry system does not occlude an overhead camera used for tracking the biological fish during an experiment [35]. However, this design does not transfer power to the lure, which necessitates a separate power supply on board. This design also does not allow for vertical or pitching motion of the lure and is thus limited to planar experiments.

The ability to use an end-effector or lure with the ability to pitch and/or move vertically could be especially important when studying larger fish species such as archer fish. Archer fish exhibit complex social behaviors beyond schooling. Known for their ability to squirt water at insects to knock them off of overhanging branches [45], they are also known to modulate their behavior based on a number of social factors, including whether other fish are present in their hunting area [46]. Investigating this type of behavior using a robotic facsimile similar to the one proposed in [34] might offer some insight into the nature of what mechanisms govern social behavior, but that platform is not capable of the precise tilting behavior archer fish use when preparing to shoot [45].

The present study outlines the design of a open-source robotic platform, named the XIZφθ Fish, that extends the capabilities of those already present in the fish-robot interaction literature. The platform allows the robot to move in three dimensions, rotate about two axes (yaw and pitch), and is designed to be flexible with respect to configuration space, lure design and functionality, and motion capability. The XIZφθ Fish’s overall architectural design adopts an approach successfully used in prior studies [47,28,48,34,24,49–52], whereby the lure’s motion is controlled by an overhead gantry onto which the lure is connected by a vertical rod. The main advantage of this approach is that it facilitates the design of a motion platform that can control the Z-position and pitch of the lure. The disadvantages of this approach are that an overhead gantry may be seen by the live fish and can thus affect their behavior, the vertical rod may also be seen by the live fish, and the overhead gantry complicates the use of an overhead camera for motion tracking. Ultimately, despite the given disadvantages, the decision to use an overhead gantry was made because the platform’s motion capability was prioritized and because of the success of other studies using an overhead gantry. Although designed for conspecific interaction studies with Banded Archer Fish (Toxotes jaculatrix), the platform design prioritizes versatility and extensibility. The experimental versatility of the platform is provided by the five degrees of freedom of the lure as well as the ability to have an actuated caudal (tail) fin. The open source nature of this platform’s hardware and software makes its extensibility a particular advantage over other ethorobotic fish in the literature. The platform can be modified for studies with other species and the lure can be designed to be a conspecific, a predator, or a prey species depending on the needs of a particular study.

Table 1 compares of the motion capabilities of the robotic platform described in the current study with those used in previous ethorobotic fish studies. The table organizes previous studies of fish-robot interactions into three groups: fixed lures, single and fixed trajectory lures, and mobile lures. “Fixed lures” are those whose center of gravity (CG) were fixed during single experimental trials, most often by a vertical rod extending upward from the lure. “Single and fixed trajectory lures” are those whose CG followed a straight or curved path that didn’t not change during single experimental trials. “Mobile lures” are those whose CG moved freely within the multidimensional configuration space of the robotic platform controlling the position of the lure. The table does not include free-swimming or self-propelled lures, such as those described in [29,23,30]. In comparison with other robotic platforms for controlling mobile lures, the XIZφθ Fish is the only platform that combines control of yaw angle and three-dimensional CG position with an articulated tail fin. It further expands on previous systems by adding another gross-motion degree of freedom: the pitch angle of the lure. Although not shown in Table 1, the XIZφθ Fish is also the only platform enabling the wired transmission of power and data to and from the lure. However,
although it does not allow for lure motion in the Z direction, the “RiBot” [44] lure designed to study zebrafish-robot interactions features an onboard battery and a motorized tail fin that is controlled wirelessly by IR communication. Notably, to the authors’ knowledge, no currently described ethorobotic systems have been open-sourced. However, Landgraf et al. report in [60] that they will soon open-source the hardware and software of “Robofish.”.

The XYZθ Fish is designed specifically to allow research groups to contribute to the ethorobotic fish literature without having to invest considerable time and money into designing their own robotic platform. As such, this paper includes detailed step-by-step build instructions, a comprehensive Bill of Materials (BOM), and operation instructions for the software used to control the platform for the validation experiments. The XYZθ Fish costs approximately 1550 USD and its fabrication requires access to only a hobbyist-level 3D printer and basic hand tools. The source repository (https://osf.io/yz6x7) contains every 3D printed component of the design and a complete assembly of the platform in a vendor-neutral format (IGES), which enables the design to be readily modified. Additionally, the source repository contains the schematic, board layout, and Gerber files required to reproduce and/or modify the custom motor controller.

2. Hardware description

2.1. Mechanical subsystem description

The XYZθ Fish is a five degree of freedom robotic motion platform whose five orthogonal axes are configured as shown in Fig. 1. The first two joints of the motion platform are prismatic and move the fish in the XY plane. The Y-Stage is composed of two motorized carriages that support the X-carriage, and every other axis is driven by a single motor. The next joint is rotary and controls the yaw angle, ψ, of the fish. The next joint is prismatic and controls the height (Z-direction) of the fish. The final joint is rotary and controls the pitch, θ, of the fish body. Additionally, the XYZθ Fish was designed to enable the passage of wires into the body of the fish, which facilitates motorizing of the tail fin with a servo motor or by other actuation approaches.

The X, Y, Z, ψ, and θ Stages are driven by geared DC motors (brushed) that feature rotary encoders. This approach to driving each stage was adopted because brushed DC motors are straightforward to drive (in comparison with stepper motors and brushless DC motors), the included encoders readily enable closed-loop position control, and importantly, the motors are available in a range of gear ratios that increase the versatility and extensibility of the platform. The motors for the X, Y, Z, and ψ stages are available in ten gear ratios ranging from [1:1] to [150:1]. The motor for the θ-Stage is available in thirteen gear ratios ranging from [5:1] to [100:1].

A detailed description of each axis and the fish lure follows.

2.1.1. Y-Stage

The Y-Stages, one of which is shown in Fig. 2, are belt-driven linear translation stages that control the y-position of the fish. Each Y-Stage Carriage is supported by a single cylindrical shaft. When assembled, the X-stage shafts fully constrain each Y-Stage to motion in the Y-direction only. The DC motors driving the Y-Stage Carriages have a gear ratio of 50:1 and are
equipped with rotary encoders having a resolution of 64 counts per resolution, if both the rising and falling edges of the encoder's two outputs are captured. The pitch diameter of the Y-Stage pulley is 1.019 inches (2.588 cm). Thus, the Y-Stage displacement measurement resolution is 0.001 inches (0.0254 mm). The maximum Y-Stage Carriage displacement is approximately 15.5 inches (39.4 cm). If the maximum permissible displacement in the y-direction is less than 15.5 inches (i.e. the tank width is less than 15.5 inches), there are two limits switches on each Y-Stage that can be adjusted to reduce the range of Y-Stage Carriages' motion.

The Y-Stage is readily customizable in several ways. To increase the displacement range, only a longer support shaft, Y-Stage belt, and aluminum extrusion are needed. The speed of the Y-Stage may be adjusted by increasing the pitch diameter of the Y-Stage Pulleys or by reducing the gear ratio of the DC motor. However, there is a trade-off between the Y-Stage speed and its displacement measurement resolution.

2.1.2. X-Stage

The X-Stage, shown in Fig. 3, is a belt-driven linear translation stage. The X-Stage is supported by two shafts that are mounted to the two Y-Stages. The Y-stages also anchor the X-Stage belt. The X-Stage belt is routed around two idler pulleys and the driven X-Stage Pulley. Like the Y-Stage Pulley, the X-Stage pulley has a pitch diameter of 1.019 inches (2.588 cm). The X-Stage Motor is equipped with an 18.75:1 gearbox and an encoder with a resolution of 64 counts per revolution if the encoders are read in full quadrature mode. The resulting X-Stage displacement measurement resolution is approximately 0.0029 inches (0.073 mm). The X-Stage has two limit switches that disable the X-Stage motor such that it will not rotate to move the X-Stage in the direction of the depressed limit switch. Features on the Y-Stages are designed to depress the
X-Stage limit switches and prevent the X-Stage from colliding with the Y-Stage. The maximum distance the X-Stage can travel is approximately 42 cm. If the maximum permissible displacement of the X-Stage is less than 42 cm (i.e. the tank length is less than 42 cm), optional components designed to depress the limit switches may be mounted on the two supporting shafts and adjusted to limit the motion of the X-Stage.

The X-Stage is customizable in the same manner as the Y-Stage. The maximum range the X-Stage can travel may be adjusted by lengthening or shortening the X-Stage belt, the two supporting shafts, and the two aluminum extrusions that traverse the x-direction of the frame. The speed of the X-Stage may be adjusted by increasing the pitch diameter of the X-Stage Pulley or by reducing the gear ratio of the DC motor.

2.1.3. $\psi$-Stage

The yaw angle, $\psi$, of the fish is controlled by the $\psi$-Stage, which is shown in Figs. 3 and 4. The $\psi$-Stage is a rotary belt driven stage with components that, as shown in Fig. 4, sandwich the X-Stage and are supported by thrust bearings which are integrated into the components. The pitch diameter of the pulley on the $\psi$-Stage Motor is 0.611 inches (1.55 cm). The pitch diameter of the larger, driven pulley centered on the rotation axis is 1.53 inches (3.89 cm). This results in a gear ratio of approximately 2.50. The $\psi$-Stage Motor has a gear ratio of 18.75:1 and an encoder with a resolution of 64 counts per revolution, if read using full quadrature. The resulting $\psi$-Stage angle measurement resolution is 0.12 degrees (0.0021 radians). A single limit switch is used to zero the $\psi$-Stage stage. A slip-ring like electrical connection is used to transmit power and data to the motion stages supported by the $\psi$-Stage, which include the Z-Stage, $\theta$-Stage, and the servo motor used to produce tail fin motion. As a result, the $\psi$-Stage may rotate indefinitely in either direction without causing any wire to get wrapped or strained. The $\psi$-Stage may be customized by changing the gear ratio of the DC motor, enabling faster rotation or increased angle measurement.

2.1.4. Z-Stage

The Z-Stage is also shown in Fig. 3. A length of square tubing is pinched by two pulleys made of a compliant material, thermoplastic polyurethane (TPU). One of these acts as an idler and the other is driven by the Z-Stage Motor. The top of the square tubing connects to the $\theta$-Stage and the bottom of the square tubing connects to a stainless steel cylinder upon which the fish is mounted. A square to cylindrical adapter holds the two components together while allowing the passage of wires. This adapter also features a tab designed to depress the Z-limit switch when the maximum height of the stage is reached. The Z-Stage Motor has a gear ratio of 102.083:1 and an encoder with 64 counts per revolution. For each revolution of the Z-Stage pulley, the fish travels approximately 6.72 cm, leading to a Z-stage measurement resolution of approximately 0.00013 mm. The high gear ratio of the motor was selected because of the high torque required to rotate the driven pulley when the pair of pulleys are firmly gripping the square tubing, causing them to elastically deform as they rotate.

2.1.5. $\theta$-Stage

The pitch angle, $\theta$, of the fish is controlled by the $\theta$-Stage (Fig. 5), which is a pulley-driven axis. Two antagonistically configured lengths of monofilament are secured on the $\theta$-Stage pulley and run the length of the square tubing and glass cylinder, where they connect to the fish. The $\theta$-Stage pulley has a 25.4 mm diameter and the monofilament attachments on the fish with a spacing of 25.4 mm. The DC motor driving the pulley has a gear ratio of 248.98:1 and an encoder having a resolution of 12 counts per revolution, which results in a $\theta$ measurement resolution of 0.121 degrees (0.002 radians). The range of motion of the $\theta$-Stage is limited to approximately 270 degrees by two limit switches that are depressed by a tab on the pulley.
at its extreme angles. Like the $\psi$-Stage, the $\theta$-Stage may be customized by changing the gear ratio of the DC motor, enabling faster rotation or increased angle measurement.

2.1.6. The Fish

The fish provided with the design files is shown in Fig. 6. The fish has a length of approximately 6.8 inches (17.4 cm) and a maximum width of approximately 1.5 inches (3.8 cm). The tail fin of the fish is actuated by a waterproof servo with a 180 degree range of motion. The fish connects to the motion platform by a hinged joint fixed to a cylinder that translates in X, Y, and Z and rotates about its axis ($\psi$). The hinged joint connection enables the motion of the fifth degree of freedom, the pitch angle ($\theta$), of the fish. This motion is driven by two lengths of monofilament that are fixed within the body of the fish, run the length of the cylinder and square tubing, and connect to the $\theta$-Stage.

Any fish model may be attached to the rod and controlled by the hardware if the body of the fish is designed to interface with the hinge joint. If the pitch angle of the fish need not change, then the fish needs only to be designed such that it can attach to the cylinder. The cylinder allows for the passage of electrical wires to the body of the fish, enabling device-compatible fish to have sensors, actuators, and other electronic components.

The wires for the waterproof servo that drives the tail fin pass through the length of the vertical cylinder that supports the lure. These wires cannot readily be hidden from the focal fish and may impact fish-robot interaction. Nonetheless, the presented embodiment of the $XYZ\psi\theta$ Fish includes a powered tail fin for two reasons: one, previous studies have demonstrated that tail fin actuation has an impact on fish-robot interaction (such as [20,26,21,25,22,28,24,23,27]) and two, research groups
may easily use a clear plastic rod and have a static tail fin (as in [34]) if the visibility of the supporting rod or wires is not acceptable. Instructions for implementing this alternative embodiment are provided in Step 5.22 of the Build Instructions.

2.2. Electrical subsystem description

2.2.1. Electrical system architecture

The electrical components handling the information and power flow throughout the robot were designed to be as modular as possible. Communication between a “master” microcontroller and a host PC is achieved using USB and a simple serial call and response protocol. The PC provides the robot with six goal positions (one for each axis plus one for the robot’s tail position) and the master microcontroller responds with the current positions of all axes. The master microcontroller then sends the requested position for each axis to the appropriate axis’s motor controller. Each motor controller receives reference commands in an interrupt service routine via I2C communication, and otherwise maintains its current reference command using closed-loop feedback control. This assures that the loop time of each individual axis’s control algorithm is not affected by how frequently commands are being sent to or from the PC.

The connections between the master and motor controllers consist of a 4-conductor bus. The bus transfers high voltage (up to 12 V) for the motor drivers, ground, and the “SDA” and “SCL” lines for I2C communication. The physical configuration of the bus and motor connections between each of the motor controllers, the master, and the PC is shown in Fig. 7.

The bus that connects the master microcontroller to each motor controller carries 12 V supplied by a fixed PC-style power supply as shown in Fig. 7. Each of the custom motor control boards described in Section 2.2.2 regulates this supply down to 5 V to operate the microcontroller and communication logic. The 12 V supply feeds the H-bridge motor drivers on each printed circuit board (PCB) to drive each axis. During normal operation, the average total current used by all 7 PCBs (master plus one PCB for each axis except for Y, which uses two) is under 5A.

2.2.2. Custom motor controller electronics

To keep costs low, keep the design as reconfigurable as possible, and because many commercially-available options for small, brushed DC motor control are either inadequate, too large, or too expensive, a custom PCB was designed to control each axis. The board includes the sensing, motor control, communication, voltage regulation, and processing capabilities needed to run closed-loop control on a brushed DC motor while providing feedback to the master microcontroller over I2C. The design was meant to provide a platform flexible enough to be used for each of the 6 motor controllers and the master, including the θ-axis controller, which also uses a common hobby servo connection to power and control the fish’s caudal fin. In total, seven copies of this board are required for the construction of the robot.

Some of the functionality built into the board and shown in Fig. 8 is not required for the configuration of the robot described in this paper. The Analog feedback input, servo/PWM input, and voltage divider circuits were included to increase the extensibility and flexibility of the design but are not used. The MicroUSB connection allows for independent logging and communication with each axis, but this connection is not required since communication with the master PCB is established through the Power and Data Bus connection via I2C.

While seven of these PCBs are required for the construction of the robot, the unit designated as the master does not use the motor control electronics, and the other six do not use the 12 V power input connector, since power is transmitted over the bus connection that connects each board as shown in Fig. 7.

![Fig. 7. Electrical system architecture.](image-url)
3. Design files

All of the files required to produce the XYZ-wh-Fish are available in the Open Science Framework Repository, located at https://osf.io/yz6x7. The repository includes the source and manufacturing files for the custom electronics, a complete bill of materials, source files for all printable components, firmware for the motor control electronics and master controller boards, and the GUI software written for robot operation. All files are open-sourced under the GPLv3 license. Table 3 describes the software and electronics files in the repository, and Table 2 describes the 3D files needed to reproduce all FDM-printed parts in the design. Each component to be printed is labeled with a part identifier which is referred to in the Build Instructions sections in square brackets.

4. Bills of materials

Bills of Materials, separated by vendor, are given in Tables 4–10. The total cost amounts to approximately 1500 USD, which includes every required component except for the custom PCBs for the motor controllers, which cost on the order of 50–100 USD depending on the manufacturer. The costs of fasteners (Table 4), which often come in packs of 50 or greater, are not prorated. In each BOM, the leftmost column has a part identification which is referred to in the Build Instructions section for clarity. The Bill of Materials for the components that populate the custom motor controller PCB is given in Table 6 (row three, item DK3, to end of table) and the quantities account for the need to create six motor controllers and one master controller. See Table 5.

5. Build instructions

To build the XYZ-wh-Fish, there is no requirement for specialized equipment except for a hobbyist-level 3D printer. There is a requirement for basic tools such as a rotary cutter, soldering iron, heat gun, calipers, flush cutters, inch and metric allen key sets, pliers, and other small hand tools. In the following build instructions, every printed part and component is given an identifier that refers to leftmost column of the design file tables or bills of materials. These identifiers are included for clarity and appear in square brackets. A complete assembly of the XYZ-wh Fish is available as an IGES file in the Open Science Framework repository (https://osf.io/yz6x7), which can be opened by most CAD software packages. The complete assembly can be referred to during construction to check the location of every mechanical component.

5.1. Custom PCBs

In total, seven custom PCBs need to be created: one master controller, and six motor controllers. The placement of components for these PCBs is given in the silkscreen layer of the board (Fig. 9). The orientation of components with polarity (LEDs, flyback diodes, electrolytic capacitor, etc) is also shown in the silkscreen layer.

For the master controller, many components are not required to be soldered onto the PCB. The components that can be excluded are the motor driver [U1] and its related electronics [D2, D4, D5, D6, D10, D11, D12, R11, R12, and R13], and the 6 V...
Table 2
Printable components. All files are available at https://osf.io/yz6x7/ under the GPL-3.0 license.

| Part # | File Name                                      | QTY |
|--------|-----------------------------------------------|-----|
| D1     | Y-StageIdlerPulleyMount.iges                 | 1   |
| D1m    | Y-StageIdlerPulleyMountMirrored.iges         | 1   |
| D2     | Y-StageIdlerPulley.iges                      | 2   |
| D3     | Y-StageCarriage.iges                         | 2   |
| D4     | Y-StageShaftMount.iges                       | 1   |
| D4m    | Y-StageShaftMountMirrored.iges               | 1   |
| D5     | Y-StageBearingRetainer.iges                  | 4   |
| D6     | Y-StageMotorMount.iges                       | 1   |
| D6m    | Y-StageMotorMountMirrored.iges               | 1   |
| D7     | X-StageShaftFixture.iges                    | 2   |
| D8     | Y-StageLimitSwitchMount.iges                 | 4   |
| D9     | X-Stage.iges                                 | 1   |
| D10    | Psi-StageBaseTop.iges                        | 1   |
| D11    | Psi-StageBaseBottom.iges                    | 1   |
| D12    | Psi-StageMotorMount.iges                    | 1   |
| D13    | Z-StageMotorMount.iges                      | 1   |
| D14    | Psi-StageTop.iges                            | 1   |
| D15    | Psi-StagePulley.iges                         | 1   |
| D16    | Psi-StageBottom.iges                         | 1   |
| D17    | RotatingBusConnector.iges                   | 1   |
| D18    | BusConnectorMount.iges                       | 1   |
| D19    | X-StageLimitMount.iges                       | 1   |
| D19m   | X-StageLimitMountMirrored.iges               | 1   |
| D20    | X-BeltIdler.iges                             | 2   |
| D21    | ZPulleyIdler.iges                            | 1   |
| D22    | ZPulleyMotor.iges                            | 1   |
| D23    | RotatingElectronicsDrum.iges                 | 1   |
| D24    | ControllerShelf.iges                         | 1   |
| D25    | Z-StageLimitMount.iges                       | 1   |
| D26    | FishHead.iges                                | 1   |
| D27    | HingeJointTop.iges                           | 1   |
| D28    | HingeJointBottom.iges                        | 1   |
| D29    | UpperCoupler.iges                            | 1   |
| D30    | LowerCoupler.iges                            | 1   |
| D31    | FishBody.iges                                | 1   |
| D32    | TailFin.iges                                 | 1   |
| D33    | ThetaStagePulley.iges                        | 1   |
| D34    | ZStageLimitSwitchExtender.iges               | 1   |
| D35    | ThetaStageMotorMount.iges                   | 1   |
| D36    | X-BeltHolderTop.iges                         | 1   |
| D36m   | X-BeltHolderTopMirrored.iges                 | 1   |
| D37    | X-BeltHolderBottom.iges                     | 1   |
| D37m   | X-BeltHolderBottomMirrored.iges              | 1   |
| D38    | ElectronicsCase.iges                         | 4   |
| D39    | ElectronicsCover.iges                        | 4   |
| D40    | XandPsiStageElectronicsMount.iges           | 1   |
| D41    | ElectronicsCoverCap.iges                    | 4   |
| D42    | MasterElectronicsMount.iges                 | 1   |
| D43    | MasterElectronicsCase.iges                  | 1   |

Table 3
Electronics design files and firmware. All files are available at https://osf.io/yz6x7/ under the GPL-3.0 license.

| Description                                      | File Name and Location                                      |
|--------------------------------------------------|------------------------------------------------------------|
| Gantry Control GUI                               | Control_GUI/gantry_control.py                              |
| Master MCU firmware                             | Arduino/master/master.ino                                  |
| X motor axis firmware                            | Arduino/axis_x/axis_x.ino                                   |
| Right Y motor axis firmware                      | Arduino/axis_yright/axis_yright.ino                        |
| Left Y motor axis firmware                       | Arduino/axis_yleft/axis_yleft.ino                          |
| Z axis motor MCU firmware                        | Arduino/axis_z/axis_z.ino                                   |
| Yaw axis motor MCU firmware                      | Arduino/axis_yaw/axis_yaw.ino                              |
| Tilt/tail axis motor MCU firmware                | Arduino/axis_tail/axis_tail.ino                            |
| Master/Axis electronics schematic file           | Electronics_Files/Eagle/servocontroller.sch               |
| Master/Axis electronics board file               | Electronics_Files/Eagle/servocontroller.brd                |
| Master/axis electronics gerber files             | Electronics_Files/servocontroller-gerber.zip               |
headers should point outward from the center of each PCB. For the Z-Stage controller and the

 headers should be soldered onto the PCBs for the motor, the two limit switches, and the two i2c bus connections. These

 labeled "POLOLU" on silkscreen) or the limit switches (2 position headers labeled "LIM1" and "LIM2" on silkscreen).

 regulator [IC2]. Additionally, there is no requirement to solder the header pins for the motor (6 position single-row header

 labeled “POLOLU on silkscreen) or the limit switches (2 position headers labeled “LIM1” and “LIM2” on silkscreen).

 For all of the motor controllers, with the exception of the Z-Stage controller and the θ-Stage controller, 90-degree male

 headers should be soldered onto the PCBs for the motor, the two limit switches, and the two i2c bus connections. These

 headers should point outward from the center of each PCB. For the Z-Stage controller and the θ-Stage controller, straight

 male headers should be soldered onto the PCB for the bus, motor, and limit switch connections.

 The θ-Stage motor controller also controls the servo motor that drives the tail fin of the fish. This is the only PCB onto

 which the 6 V regulator needs to be soldered. Additionally, a three position straight male header needs to be soldered at

 the location labeled “SERVO OUT” on the silkscreen (located near center of board under the hole).

### Table 4
BOM for McMaster, part one: fasteners.

| Item | Component Description | Part #     | Unit | Cost  | QTY |
|------|------------------------|------------|------|-------|-----|
| F1   | 18–8 Stainless Steel Socket Head Screw, 1–72 Thread Size, 1/2" Long | 92196A069 | Pack of 50 | $4.46 | 1   |
| F2   | 18–8 Stainless Steel Socket Head Screw, 4–40 Thread Size, 1" Long, Partially Threaded | 92196A115 | Pack of 100 | $5.54 | 1   |
| F3   | 316 Stainless Steel Washer, Number 2 Screw Size, 0.094" ID, 0.25" OD | 90730A003 | Pack of 200 | $0.33 | 1   |
| F4   | 18–8 Stainless Steel Narrow Hex Nut, 2–56 Thread Size | 92185A089 | Pack of 50 | $7.70 | 1   |
| F5   | 18–8 Stainless Steel Socket Head Screw, 5–40 Thread Size, 7/8" Long | 92185A086 | Pack of 50 | $8.61 | 1   |
| F6   | 18–8 Stainless Steel Socket Head Screw, Number 2 Screw Size, 0.094" ID, 0.25" OD | 90107A003 | Pack of 100 | $3.66 | 1   |
| F7   | 18–8 Stainless Steel Washer for Number 1 Screw Size, 0.08" ID, 0.156" OD | 92141A211 | Pack of 50 | $4.51 | 1   |
| F8   | 18–8 Stainless Steel Socket Head Screw, 5–40 Thread Size, 1/4" Long | 92196A077 | Pack of 100 | $6.27 | 1   |
| F9   | 18–8 Stainless Steel Socket Head Screw, 5–40 Thread Size, 1/2" Long | 92196A081 | Pack of 100 | $6.44 | 1   |
| F10  | Super-Corrosion-Resistant 316 Stainless Steel, Socket Head Screw, 5–40 Thread Size, 5/8" Long | 92185A089 | Pack of 50 | $7.70 | 1   |

### Table 5
BOM for McMaster, part two.

| Item | Component Description | Part #     | Unit | Cost  | QTY |
|------|------------------------|------------|------|-------|-----|
| M1   | Green Plastic 5" × 20" Shim Sheet, 0.003" Thick | 9513K15 | Each | 3.55 | 1   |
| M2   | MXL Series Timing Belt Pulley 1/4" Maximum Belt Width, Corrosion-Resistant, 1.21" OD | 1375K55 | Each | 15.98 | 3   |
| M3   | MXL Series Timing Belt Pulley 1/4" Maximum Belt Width, Corrosion-Resistant, 0.79" OD | 1375K45 | Each | 11.73 | 1   |
| M4   | MXL Series Timing Belt 1/4" Width, Trade No. 91mxl025 | 7887K223 | Each | 3.57 | 1   |
| M5   | 1/4" Width MXL Series No. Ll025mxl Timing Belt | 7959K21 | Foot | 2.42 | 12  |
| M6   | Self Aligning Linear Ball Bearing High-Load, Acetal with Steel Ball, for 3/8" Shaft Diameter | 6489K62 | Each | 21.58 | 8   |
| M7   | External Retaining Ring 3/8" Shaft Diameter | 9968K23 | Each | 0.42 | 8   |
| M8   | 18–8 Stainless Steel Dowel Pin 1/8" Diameter, 2" Long | 90145A480 | Pack of 10 | 5.59 | 1   |
| M9   | Delrin® Acetal Resin Ball 1/4" Diameter | 9614K24 | Pack of 100 | 8.75 | 1   |
| M10  | Highly Corrosion-Resistant 316/316L Stainless Steel Rod 3/8" Diameter | 89325K93 | Each (3 ft length) | $14.79 | 2   |
| M11  | Weldable 122 Copper Tube 0.014" Wall Thickness, 1 Foot Long, 1/16" OD | 7190K51 | Pack of 3 | $2.93 | 1   |
| M12  | Light Duty Dry-Running Nylon Sleeve Bearing 1/16" Thick Flange, 3/8" Shaft, 1/2" Housing ID, 3/4" Long | 6389K624 | Each | $0.94 | 4   |
| M13  | 304/304L Stainless Steel Rod 3/8" Diameter | 89535K837 | Each (2 ft length) | 9.9 | 2   |
| M14  | Clear Polycarbonate Rectangle Tube 1/2" × 1/2" Outside Size, 6 Feet Long | 3161T11 | Each | 19.26 | 1   |
| M15  | Smooth-Bore Seamless 316 Stainless Steel Tubing 1/4" OD, 0.028" Wall Thickness | 8978SK823 | Each (3 ft length) | 19.65 | 1   |
| M16  | White Delrin® Acetal Resin Tube Tight-Tolerance, 1/8" OD × 1/16" ID | 8627K119 | Each (3 ft length) | 3.48 | 1   |

Total $384.63

Total $116.15
### Table 6
BOM for Digikey.

| Item | Component Description | Part # | Unit | Cost  | QTY |
|------|-----------------------|--------|------|-------|-----|
| DK1  | ADAPT SPADE LUG TO BAN JCK BLK/R | 501-2457-ND | Each | $6.59 | 1 |
| DK2  | SWITCH SNAP ACTION SPDT 16A 250 V | 480-2999-ND | Each | $3.36 | 1 |
| DK3  | CAP TANT POLY 2.2UF 35 V | 478-6640-1-ND | Each | $1.70 | 7 |
| DK4  | TERM BLOCK 2POS 45DEG 3.5MM PCB | 277-1779-ND | Each | $0.48 | 7 |
| DK5  | CAP ALUM 220UF 20% 35 V SMD | 403-2205-1-ND | Each | $0.50 | 14 |
| DK6  | CONN HEADER R/A 40POS 2.54MM | S1311EC-40-ND | Each | $0.97 | 7 |
| DK7  | CONN HEADER VERT 6POS 2.54MM | 609-3210-ND | Each | $0.42 | 7 |
| DK8  | TERM BLOCK 2POS 45DEG 3.5MM PCB | 277-1779-ND | Each | $0.48 | 7 |
| DK9  | RES SMD 10 K OHM 0.1% 1/10 W | RR12P10.0KDCT-ND | Each | $0.11 | 7 |
| DK10 | CRYSTAL 16.0000MHZ 18PF SMD | 535-9122-1-ND | Each | $0.63 | 7 |
| DK11 | RES SMD 1 M OHM 0.1% 1/8 W 0805 | P1MDACT-ND | Each | $0.36 | 7 |
| DK12 | CAP CER 0.1UF 50 V SMD | 493-2205-1-ND | Each | $0.50 | 14 |
| DK13 | RES SMD 1 M OHM 0.1% 1/8 W 0805 | P1MDACT-ND | Each | $0.36 | 7 |
| DK14 | IC REG LINEAR 6 V 1A TO220CP-3 | BA7806CP-E2CT-ND | Each | $0.86 | 7 |
| DK15 | IC MCU 8BIT 32 KB FLASH ADF4125 | 609-4618-6-ND | Each | $0.42 | 7 |
| DK16 | WIRE RED CLEAR CHIP SMD | 160-1457-1-ND | Each | $0.34 | 14 |
| DK17 | 0.1" (2.54 mm) Crimp Connector Housing: 2-Pin 25-Pack | 397-2940-5-ND | Each | $0.69 | 1 |
| DK18 |250:1 Micro Metal Gearmotor HPCB 12 V with Extended Motor Shaft | 3055 | Each | $18.95 | 1 |
| DK19 | Magnetic Encoder Pair Kit for Micro Metal Gearmotors | 3081 | Each | $9.55 | 1 |
| DK20 | 19:1 Metal Gearmotor 37Dx70L mm with 64 CPR Encoder | 2822 | Each | $39.95 | 3 |
| DK21 | 50:1 Metal Gearmotor 37Dx70L mm with 64 CPR Encoder | 2824 | Each | $39.95 | 1 |
| DK22 | Snap-Action Switch with 16.7 mm Lever: 3-Pin, SPDT, 5A | 1402 | Each | $1.15 | 5 |
| DK23 | 100:1 Metal Gearmotor 37Dx73L mm with 64 CPR Encoder | 2826 | Each | $39.95 | 1 |
| DK24 | Mini Snap-Action Switch with 13.5 mm Lever: 3-Pin, SPDT, 1A | 1528 | Each | $0.99 | 3 |

**Total:** $171.37

### Table 7
BOM for Pololu.

| Item | Component Description | Part # | Unit | Cost  | QTY |
|------|-----------------------|--------|------|-------|-----|
| PL1  | Wires with Pre-Crimped Terminals 50-Piece 10-Color Assortment F-F 6" | 1800 | Pack of 50 | $9.95 | 1 |
| PL2  | Wires with Pre-Crimped Terminals 50-Piece 10-Color Assortment F-F 12" | 1803 | Pack of 50 | $17.49 | 1 |
| PL3  | Wires with Pre-Crimped Terminals 50-Piece 10-Color Assortment F-F 24" | 2006 | Pack of 50 | $24.95 | 1 |
| PL4  | Wires with Pre-Crimped Terminals 20-Piece 10-Color Assortment F-F 36" | 2000 | Pack of 20 | $17.49 | 2 |
| PL5  | Wires with Pre-Crimped Terminals 10-Color Assortment M-M 3" | 1808 | Pack of 50 | $9.95 | 1 |
| PL6  | Wires with Pre-Crimped Terminals 6-Piece 6-Color Assortment M-M 1" | 3962 | Pack of 60 | $8.95 | 1 |
| PL7  | Wires with Pre-Crimped Terminals 10-Color Assortment M-M 6" | 1801 | Pack of 50 | $9.95 | 1 |
| PL8  | 0.1" (2.54 mm) Crimp Connector Housing: 1 × 6-Pin 10-Pack | 1905 | Pack of 10 | $0.79 | 1 |
| PL9  | 0.1" (2.54 mm) Crimp Connector Housing: 1 × 4-Pin 10-Pack | 1903 | Pack of 10 | $0.59 | 3 |
| PL10 | 0.1" (2.54 mm) Crimp Connector Housing: 1 × 2-Pin 25-Pack | 1901 | Pack of 25 | $0.69 | 1 |
| PL11 | 250:1 Micro Metal Gearmotor HPCB 12 V with Extended Motor Shaft | 3055 | Each | $18.95 | 1 |
| PL12 | Pololu Micro Metal Gearmotor Bracket Extended Pair | 1089 | Pack of 2 | $4.95 | 1 |
| PL13 | Magnetic Encoder Pair Kit for Micro Metal Gearmotors | 3081 | Pack of 2 | $9.55 | 1 |
| PL14 | 19:1 Metal Gearmotor 37Dx88L mm with 64 CPR Encoder | 2822 | Each | $39.95 | 3 |
| PL15 | 50:1 Metal Gearmotor 37Dx70L mm with 64 CPR Encoder | 2824 | Each | $39.95 | 1 |
| PL16 | 100:1 Metal Gearmotor 37Dx73L mm with 64 CPR Encoder | 2826 | Each | $39.95 | 1 |
| PL17 | Snap-Action Switch with 16.7 mm Lever: 3-Pin, SPDT, 5A | 1402 | Each | $1.15 | 5 |
| PL18 | 100:1 Metal Gearmotor 37Dx73L mm with 64 CPR Encoder | 2826 | Each | $39.95 | 1 |

**Total:** $359.83

### Table 8
BOM for Amazon.

| Item | Component Description | Link | Unit | Cost  | QTY |
|------|-----------------------|------|------|-------|-----|
| AZ1  | HATCHBOX PLA 3D Printer Filament | Link | Each | $19.99 | 1 |
| AZ2  | NinjaTek Cheetah TPU filament, 1.75 mm | Link | Each | $30.96 | 1 |
| AZ3  | MG Chemicals Carbon Conductive Assembly Paste, 1 oz Jar | Link | Each | $18.59 | 1 |
| AZ4  | MG Chemicals #3 No Clean Super Wick Desoldering Braid | Link | Each | $6.49 | 1 |
| AZ5  | Traxxas Summit Waterproof 2065 Micro SERVO | Link | Each | $30 | 1 |
| AZ6  | Berkley Trilene XT Monofilament Fishing Line (250 yard/ 25 lb) | Link | Each | $8.29 | 1 |
| AZ7  | 25ft - 1/4 inch Flexo PET Expandable Braided Sleeving - Black | Link | Each | $6.81 | 1 |
| AZ8  | NTE Heat Shrink 2:1 Assorted Colors and Sizes 160 PCS | Link | Each | $12.99 | 1 |

**Total:** $134.12
5.2. Programming each axis

At this stage, it is critical to install the Arduino bootloader on each motor controller and the master. Installing the bootloader, particularly for the Z-Stage and θ-Stage controllers, requires the mechanical system to be extensively disassembled if this step is saved for the end of the build. While this is true for the bootloader, access to the USB programming ports of all microcontrollers is available after completing the build instructions.

Before completing the steps below, you must install the "Pololu A Star 32U4" board option in the Arduino IDE using the Boards Manager tool. Further, the "Pololu A Star 32U4" Arduino bootloader must be installed on the AT32U4 chip on each PCB. This can be accomplished using a USBTiny programming chip and the 6-pin ISP header on each PCB according to the USBTiny’s instructions.

Because each axis of the robot requires different control gains and conversion factors, the provided software includes an Arduino “sketch” for each axis. In the software repository, there is a folder labeled for each axis that contains the required
firmware. Complete the steps below for each axis. The steps below refer to the X-axis, but the procedure is the same for all axes.

(a) Plug a micro-USB cable into the axis you wish to program, and connect the other end to your computer
(b) Open “axis_x.ino” in the Arduino IDE.
(c) Select the axis’s serial port from the Tools—Port submenu of the Arduino IDE
(d) Press the “Upload” button in the Arduino IDE.

5.3. Fabricating printed parts

The parts listed in Table 2 were designed to be printed with a hobbyist-level single-extruder Fused Deposition Modeling (FDM) based printer. As such, no part requires any support material (non-soluble or soluble). All of the printed parts in the following build instructions were sliced using Slic3r PE (with material-specific default settings) and fabricated using the Original Prusa i3 MK3 (Prusa Research).

The printing orientation of each part is indicated by the letter “X,” which is included in each model on the surface that should be placed on the printing bed. Most parts were printed with PLA material [AZ1], but the following parts were printed with semi-flexible TPU [AZ2]: D21, D22, and D29-D32.

5.4. Frame components

(a) Components Required: 20 × 20 × 1000 mm aluminum extrusions [OB2] (4X), 20 × 40 × 1000 mm aluminum extrusions [OB3] (2X), corner brackets [OB6] (24X), plates [OB5] (4X), tee-nuts [OB7] (8X), and M5 × 8 mm screws [F22] (32X).
(b) Instructions:
   i. Using two tee-nuts and M5 screws, fasten two corner brackets onto a length of 20 × 20 × 1000 mm aluminum extrusion as shown in the subassembly labeled “Diagonal Beam” in Fig. 10. The edges of the corner brackets should be flush with the ends of the aluminum extrusion.
   ii. Repeat the preceding instruction three additional times to create a total of four Diagonal Beam subassemblies.
   iii. Using four tee-nuts and M5 screws, fasten two plates onto a 20 × 40 × 1000 mm aluminum extrusion. The edges of the plates should be flush in the ends of the aluminum extrusion, as shown in the subassembly labeled “X-Direction Beam” in Fig. 10.
   iv. Using eight tee-nuts and M5 screws, fasten eight corner brackets onto the same length of aluminum extrusion. Match the spacing and orientation of the brackets shown in Fig. 10. The positions of the two sets of brackets are mirrored.
   v. Repeat the preceding two instructions to create an additional X-Direction Beam subassembly.

Fig. 10. Components of frame.
5.5. Completed frame

(a) Previously made parts required: Diagonal Beam subassemblies (4X) and X-Direction Beam subassemblies (2X).
(b) Components required: 20 × 20 × 1500 mm aluminum extrusions [OB1] (4X), tee-nuts [OB7] (16X), and M5 × 8 mm screws [F22] (16X).
(c) Instructions: Note that in the process of assembling the frame components, the correct height of the X-Direction beams must be set by the user and may vary from approximately 400 to 1400 mm.
   i. Determine the desired height for the X-Direction beams and mark the four 1500 mm lengths of aluminum extrusion accordingly.
   ii. Using four tee-nuts and M5 screws, fasten the plates of one X-Direction beam subassembly onto two of the 1500 mm lengths of aluminum extrusion, using the previously made marks to guide the placement of the plates.
   iii. Repeat the previous step once to create the two "H"-shaped faces of the frame.
   iv. Using eight tee-nuts and M5 screws, fasten the four Diagonal Beam subassemblies onto the two "H"-shaped faces to complete the frame. The adjacent pairs of Diagonal Beams should be mirrors of each other along the x-axis.
   v. As shown in Fig. 11, the center-to-center vertical distance between the tee-nuts should be approximately 405 mm. At this stage, only slightly tighten the Diagonal Beams onto the frame. Their final position will be adjusted after attaching the Y-Stages to the upward facing corner brackets.

5.6. Y-stage components

(a) Printed parts required: Y-Stage Idler Pulley Mount [D1], Y-Stage Idler Pulley Mount Mirrored [D1m], Y-Stage Idler Pulley [D2] (2X), Y-Stage Carriage [D3] (2X), Y-Stage Shaft Mount [D4], Y-Stage Shaft Mount Mirrored [D4m], Linear Bearing Cap (4X) [D5], Y-Stage Motor Mount [D6], and Y-Stage Motor Mount Mirrored [D6m].
(b) Components required: 19:1 Geared DC Motor [PL14], Y-Stage Pulley [M2], 0.003 Inch Shim [M1], Linear Bearings [M6] (2X), Retaining Clip [M7] (2X), #2 Washer [F3] (2X), M3 by 8 mm Screws [F21] (6X), M3 Washers [F23] (6X), Low Profile #2-56 Nuts [F4] (10X), #2-56 3/8 Inch Screw [F2] (14X), Nylon Bushing [M12] (2X), and a #6-32 by 1-1/4 Inch Screw [F19].
(c) Instructions:
   Note that these instructions must be completed twice, because there are two Y-Stages. The two Y-Stages are identical, but mirrored along the x-direction. Therefore, mirrored versions of the following printed components need to be fabricated: Y-Stage Idler Pulley Mount, Y-Stage Idler Motor Mount, and Y-Stage Shaft Mount. Two Y-Stage Carriages, two Y-Stage Idler Pulleys, and four Linear Bearing Caps are required in total, but there no need to mirror these parts.
   i. Y-Stage Motor Subassembly
      A. Press-fit 4 #2-56 nuts into the 4 hexagonal pockets on the Y-Stage Idler Pulley Mount, located on the rails that interface with the aluminum extrusion.
      B. Partially turn 4 #2-56 screws into the press-fitted nuts, such that the screws are engaged with but not fully through the nuts.

Fig. 11. Completed frame.
C. Fasten the Geared DC motor into the Y-Stage Motor Mount using 6 M3 screws and washers.

D. Cut a 1.5 by 0.5 inch (38 by 13 mm) piece of the shim material and place it inside of the pulley. The shim should overlap itself and traverse the inner diameter of the pulley twice. The purpose of this step is to adapt the 6 mm shaft diameter of the DC motor to the 6.35 mm (1/4 inch) inner diameter of the pulley.

E. Place the pulley onto the motor shaft, hub side first, such that the pulley is inserted as far as possible without the hub making contact with the M3 screws. Tighten the two set screws included with the pulley. One of the two set screws should engage the flat of the shaft on the geared DC motor.

iii. Y-Stage Idler Pulley Subassembly
   A. As with the Y-Stage Idler Pulley Mount, press-fit 4 #2-56 nuts into the 4 hexagonal pockets of the Y-Stage Idler Pulley Mount and partially thread 4 #2-56 screws into them.
   B. Place the Y-Stage Idler Pulley into the Y-Stage Idler Pulley Mount and, starting from the bottom on the Y-Stage Idler Pulley Mount, thread the #6-32 screws through both components. The screw should self-thread through the portion of the Y-Stage Idler Pulley Mount above the idler pulley.
   C. Press-fit the nylon bushing into the Y-Stage Idler Pulley Mount.

iii. Y-Stage Idler Pulley Mount Subassembly
   A. As with the Y-Stage Idler Pulley Mount, press-fit 4 #2-56 nuts into the 4 hexagonal pockets of the Y-Stage Idler Pulley Mount and partially thread 4 #2-56 screws into them.
   B. Place the Y-Stage Idler Pulley into the Y-Stage Idler Pulley Mount and, starting from the bottom on the Y-Stage Idler Pulley Mount, thread the #6-32 screws through both components. The screw should self-thread through the portion of the Y-Stage Idler Pulley Mount above the idler pulley.
   C. Press-fit the nylon bushing into the Y-Stage Idler Pulley Mount.

iv. Y-Stage Carriage Subassembly
   A. Insert one retaining clip onto each of the linear bearings.
   B. Insert the linear bearings (not-clipped side first) into the Y-Stage Carriage.
   C. Using two #2-56 screws and #2 washers for each, fasten the Linear Bearing Caps onto the Y-Stage Carriage to hold the linear bearing in place.

5.7. Completing the Y-Stages

(a) Previously made parts required: The four Y-Stage subassemblies shown in Fig. 12.
(b) Printed parts required: X-Stage Shaft Fixture (2X) [D7] and Y-Stage Limit Switch Mount (4X) [D8].
(c) Components required: 20 × 60 × 1000 mm aluminum extrusion [OB4], 3/8 inch by 2-ft shaft [M13], 57 in (145 cm) length of timing belt [M5], #4-40 by 0.75 inch screws [F13] (4X), #2-56 by 0.5 inch screws [F9] (4X), #2 washers [F3] (2X), #2-56 by 0.375 inch screws [F2], low profile #2-56 nut [F4], limit switches (2X) [PL17], 3 inch male-male (m-m) pre-crimped wires [PL5] (2X), and a 1 × 2 pin connector housing [PL10].
(d) Instructions: Note that these instructions must be completed twice, because there are two Y-Stages.
   i. Assemble two mounted limit switches.
      A. Cut one 3 inch m-m pre-crimped wires in half and remove some insulation from the two cut ends. Solder the exposed wires to the limit switch such that the pair are“normally-open.” Repeat this step for the second limit switch.
B. Using two #2-56 by 0.5 inch screws and two #2 washers, fasten the limit switches onto their mounts as shown in Fig. 13 (lever of switch pointed up).
C. Press-fit a #2-56 nut into the pocket of each Y-Stage Limit Switch Mount.
D. Partially thread a #2-56 by 0.375 inch screw into each of the press-fitted nuts.

ii. Clean the shafts with an all-purpose cleaner if they are dirty.
iii. Slide the Y-Stage Idler Pulley subassembly onto the aluminum extrusion approximately 6 in (15.24 mm) from the edge, as shown in Fig. 13. Tighten the four #2-56 screws to lock the position of the subassembly relative to the aluminum extrusion. Do not over-tighten the screws, which could cause their heads to shear. They only need to engage the aluminum extrusion slightly. This is true for every component that connects to an aluminum extrusion with this approach.
iv. From the opposite end of the extrusion, slide the Y-Stage Shaft Mount subassembly onto the extrusion. Place the stainless steel shaft into the nylon bearing of the Y-Stage Idler Pulley subassembly.
v. Slide the Y-Stage Carriage subassembly onto the shaft, and then position the Y-Stage Shaft Mount subassembly such that it constrains the motion of the shaft. Tighten the two screws on the Y-Stage Shaft Mount subassembly to lock it into position.
vi. Slide the two mounted limit switches onto the slide of the aluminum extrusion such that both switches face the center of the extrusion. The switches should be on the same side as the idler pulley.
vii. Slide the Y-Stage Motor Mount subassembly onto the aluminum extrusion such that the motorized pulley is on the same side of the extrusion as the idler pulley. Slide the Y-Stage Motor Mount until it abuts the Y-Stage Shaft Mount.
viii. Attach the belt to the Y-Stage Carriage as shown in Fig. 13.
ix. Tighten the belt by sliding the Y-Stage Stage Motor Mount away from the shaft support. When the belt is tensioned, lock the position of the Y-Stage Motor Mount with the 4 #2-56 screws.

5.8. Mounting the Y-Stages onto the frame

(a) Components required: M5 × 8 mm screws [F22] (16X) and tee-nuts [OB7] (16X).
(b) Instructions:
i. Place the Y-Stages onto the frame, aligning them with the corner brackets, and fasten them into place using the M5 screws and tee-nuts. The orientation of the Y-Stages should be such that the motors are closer to the diagonal beams.
ii. The ends of the 20 × 60 mm extrusions for the Y-Stages should be flush with the ends of the corner brackets. If they are not, slightly loosen the M5 screws holding the frame together to make adjustments.
iii. At this stage, the frame components can be adjusted and re-positioned as needed, and the frame can be finalized by tightening the metric screws that threaded into the tee-nut fasteners.

5.9. X-Stage

(a) Printed parts required: X-Stage [D9], ψ-Stage Base Top [D10], ψ-Stage Base Bottom [D11], and ψ-Stage Motor Mount [D12].
Components required: e-clips [M7] (4X), linear bearings [M6] (4X), #6–32 set screws [F18] (2X), #4-40 by 0.75 inch screws [F13] (4X), and 1/8 x 2 inch dowel pins [M8] (2X).

Instructions:
1. The X-Stage will print with a thin (single layer) of material blocking the holes for the X-Stage motor. Remove this material with pliers or other hand tools. The purpose of this layer is to enable the part to be printed without needing support material.
2. Place dowel pins in the ψ-Stage Motor Mount.
3. Place ψ-Stage Motor Mount on the right side of Fig. 14.
4. Place bearings into the X-stage as shown in Fig. 14. Carefully press the e-clips into the grooves of the bearing to hold them in place.
5. Place the ψ-Stage Base Top and ψ-Stage Base Bottom onto the X-Stage. The ψ-Stage Base Top has clearance holes for the dowel pins supporting the ψ-Stage Motor mount. Place the #4-40 screws through the ψ-Stage Base Top and fasten them into the ψ-Stage Base Bottom, into which they should self-thread.
6. Use the #6–32 set screws to lock the dowel pins going through the ψ-Stage Base Top in place. The set screws only need to make light contact with the dowel pins and should not be over-tightened.

5.10. Zψ-Stage

(a) Printed parts required: Z-Stage Motor Mount [D13], ψ-Stage Top [D14], and ψ-Stage Pulley [D15].
(b) Components required: #4-40 by 1 inch screws [F12] (4X).
(c) Instructions:
1. Place the four #4-40 screws through the Z-Motor Mount and ψ-Stage Pulley such that their cutouts line up. The cutouts are shown in Fig. 15.
2. Screw the #4-40 screws into the ψ-Stage Top. The screws should self-thread into the part.

5.11. Combining the X and Zψ-Stage

(a) Previously made parts required: X-Stage and Zψ-Stage.
(b) Printed parts required: ψ-Stage Bottom [D16].
(c) Components required: #6–32 by 1–1/4 inch screws [F19] (3X), #6 washers [F20] (3X), and 1/4 inch spheres [M9] (62X).
(d) Instructions:
1. Place the X-Stage and ψ-Stage Bottom on a flat surface in the orientation shown in Fig. 16 (left).
2. Place 31 spheres in the triangular grooves of each part.
3. Carefully place the Zψ-Stage onto the X-Stage and hold the components together with some pressure to prevent the spheres from falling out.
4. Carefully place the result onto the ψ-Stage Bottom and hold the three components together to prevent the spheres from falling out.

![Fig. 14. Parts for and result of building X-Stage.](image-url)
v. Rotate all three component together and place the three #6–32 bolts (with washers) through the \( \psi \)-Stage Bottom.

vi. As the #6–32 screws are tightened, they will self-thread into the \( \psi \)-Stage.

vii. Tighten the screws enough to eliminate unwanted off-axis motion, but not so much that the \( \psi \)-Stage is difficult to rotate.

5.12. Motorizing the \( \psi \)-axis.

(a) Previously made parts required: Combined X and \( \psi \)-Stage.

(b) Components required: 50:1 geared DC motor [PL15], MXL Timing Belt [M4], MXL Pulley [M3], 0.003 inch shim [M1], limit switch [DK2], 6 inch f-f pre-crimped wires [PL1] (2X), 1 \times 2 connector housing [PL10], M3 by 8 mm screws [F21] (6X), #2 washers [F3] (2X), #2-56 by 7/8 inch screw [F5] (2X), #4 washers [F14] (2X), and #4-40 by 3/4 inch screws [F13] (2X).
(c) Instructions:

i. Fasten the geared DC motor in the ψ-Stage Motor Mount with the six M3 screws.

ii. Cut a 1.5 by 0.5 inch (38 by 13 mm) piece of the shim material and place it inside of the pulley. The shim should overlap itself and traverse the inner diameter of the pulley twice.

iii. Hub side first, place the shimmed pulley onto the shaft of the geared DC motor and use the included set screws to lock its position relative to the shaft. One set screw should engage the flat of the geared DC motor shaft.

iv. Place the MXL timing belt over the Z-Stage Motor Mount and MXL pulley.

v. To set the tension of the ψ axis belt, place the two #2-56 screws (with the two #2 washers) through clearance holes in the X-Stage. The screws will self-thread into the ψ-Stage Motor Mount. Carefully adjust the tension by tightening the screws an equal number of rotations.

vi. Solder the two pre-crimped wires onto the limit switch such that the connection between them is normally-open (one on the tab labeled “C” and one on the tab labeled “NO”) and place the free ends of the wires into the 1/4 housing.

vii. Using pliers, bend the lever arm of the limit switch such that it curves away from the feature on the ψ-Stage Top that depresses it. Using the two #4-40 bolts (with the two #4 washers), fasten the limit switch to the X-Stage.

5.13. Rotating I2C bus connection

(a) Printed parts required: Rotating Bus Connector [D17].

(b) Components required: 12 inch (≈ 30 cm) length of #3 solder wick [AZ4] (4X), 6 inch female–female (f-f) pre-crimped wires [PL1] (4X: 1 red, 1 blue, 1 black, and 1 yellow), 1 x 4 connector housing [PL9], and heat shrink tubing [AZ8] (1 red, 1 blue, 1 black, and 1 yellow).

(c) Instructions:

i. Insert approximately one inch (25 mm) of a length of solder wick through a hole (from the outside to the inside) in the bottom groove (labelled red in Fig. 18) of the Rotating Bus Connector. Wrap the solder wick around the Rotating Bus Connection (keeping it flat within the groove), and insert the free end of the solder wick through the same hole. (see Fig. 17).

ii. Twist the ends of the solder wick together to keep them in place and cut any extra length of the twisted solder wick pair. There should be about 0.5 inches (13 mm) of twisted solder wick left after cutting the excess.

iii. Tin the twisted solder wick pair, tin one end of the red pre-crimped wire, and then solder the two tinned parts together. Finish the electrical connection by covering the exposed conductors with the red heat shrink tubing.

iv. Repeat the first two instructions for the black, yellow, and blue wire, in that order.

v. Insert the pre-crimped wires into the 1 x 4 wire housing in the following order: red, black, yellow, and blue.

5.14. Combining the rotating I2C bus connector with the XZψ-stage

(a) Previously made parts required: Assembled XZψ-Stage and Rotating Bus Connection.

(b) Printed parts required: Bus Connector Mount [D18].

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Fig. 17. Parts for and result of motorizing the ψ axis.
(c) Components required: #4-40 by 3/8 inch screws [F17] (7X), 6 inch f-f pre-crimped wires [PL1] (4X: 1 red, 1 blue, 1 black, and 1 yellow), 1 x 4 connector housing [PL9], heat shrink tubing [AZ8] (1 red, 1 blue, 1 black, and 1 yellow), and 4 inch (≈ 100 mm) lengths of copper tubing [M11] (4X).

(d) Instructions:

i. Use five #4-40 screws to attach the Rotating Bus Connection to the ψ-Stage Bottom. The screws should self-thread into the ψ-Stage Bottom. The Rotating Bus Connector has two holes that enable the monofilament (for tilting the fish) to pass through the ψ-Z-Stage. These holes should line up with the two holes (having the same purpose) on the ψ-Stage Bottom.

ii. Use the remaining two #4-40 screws to attach the Bus Connector Mount to the X-Stage. The screws should self-thread in the X-Stage.

iii. Tin one end of each copper tube and one end of each pre-crimped wire. Solder each pre-crimped wire to a copper tube, using the tinned ends of each component to facilitate the creation of strong solder joints. Cover each solder connection with heat shrink tubing such that the heat shrink color matches the color of the wire insulation.

iv. Push the copper tube with the red wire through the hole of the Bus Connector Mount closest to the X-Stage, such that it is pushed toward the Rotating Bus Connector. Once the copper tube comes out of the other side of the Bus Connector Mount, place a piece of red heat shrink tubing on the copper tube. As the copper tube comes into contact with the solder wick, manually rotate the Rotating Bus Connector and continue to press the copper tube through. Do not bend the copper tubes by hand. Rather, allow the drum to make contact and displace the copper tubes. Push until the copper tube cannot be pushed farther and lock the copper tube into place by shrinking the heat shrink tube.

v. Repeat the last step for the black, yellow, and blue wire, in that order. Be careful as you heat the heat shrink tubing to avoid overheating the printed components nearby.

vi. Insert the pre-crimped wires into the 1 x 4 wire housing in the following order: red, black, yellow, and blue.

vii. Check that wire colors on both sides of the Rotating Bus Connector match.

5.15. Motorizing the X-axis

(a) Previously made parts required: XZψ-Stage.

(b) Printed parts required: X-Stage Limit Switch Mounts [D19 and D19m], and X-Stage Idler Pulleys [D20] (2X).

(c) Components required: X-Stage Pulley [M2], 19:1 geared DC motor [PL14], X-Stage limit switches [DK2] (2X), and 0.003 inch shim material [M1].

(d) Hardware required: M3 by 8 mm screws [F21] (6X), M3 washers [F23] (6X), #4-40 by 3/4 inch screws [F13] (4X), #4-40 nuts [F15] (4X), #4 washers [F14] (4X), #2-56 by 3/8 inch screws [F2] (8X), and #4-40 by 1 inch screws [F12] (2X).

(e) Instructions:

i. Using the 6 M3 screws and washers, fasten the X-Stage motor to the XZψ-Stage.

ii. Cut a 1.5 by 0.5 inch (38 by 13 mm) piece of the shim material and place it inside of the pulley. The shim should overlap itself and traverse the inner diameter of the pulley twice.

iii. Flanged-side first, place the shimmmed pulley onto the shaft of the geared DC motor and use the included set screws to lock its position relative to the shaft. One set screw should engage the flat of the geared DC motor shaft.
iv. Place the 2 X-Stage Idler Pulleys as shown in Fig. 3. Hold the idler pulleys in place using the two #4-40 by 1 inch screws, which will self-thread into the X-Stage Carriage.

v. Using the 8 #2-56 by 0.375 inch screws and #2 washers, fasten the X-Stage Limit Switch Mounts onto the XZψ-Stage. If the X-Stage Limit Switch Mounts are mounted on their correct side, they will help constrain the linear bearings, as shown in Fig. 20(right), see Fig. 19.

vi. Using the 4 #4 nuts, washers, and #4-40 by 0.75 inch screws, fasten the limit switches onto the limit switch mounts. The lever arms of the switches should point up (away from the Rotating I²C Bus Connector).

vii. The lever arm of the limit switch nearest the Z-Stage motor will collide with the Z-Stage. Prevent this by manually bending the limit switch lever arm as shown in Fig. 20 (middle), see Fig. 21.
5.16. Motorizing the Z-axis

(a) Printed parts required: Z-Stage Idler Pulley [D21] and Z-Stage Driven Pulley [D22]. These parts should be printed with flexible filament [AZ2].
(b) Components required: 100:1 Geared DC Motor [PL16], M3 by 8 mm screws [F21] (6X), M3 washers [F23] (6X), 1/8 X 2 inch dowel pin [M8], and a #2-56 by 3/8 inch set screw [F11].
(c) Instructions:
   i. Using the M3 screws and washers, mount the motor onto the Z-Stage Motor Mount.
   ii. Press-fit the Z-Stage Driven Pulley onto the shaft of the motor, aligning the flat of the motor shaft with the flat of the driven pulley.
   iii. Place the #2 set screw in the hole (on the pulley) perpendicular to the flat and tighten it until it abuts the flat on the motor shaft.
   iv. Insert the dowel rod into one hole of the Z-Stage Motor Mount, press it through the Z-Stage Idler Pulley, and then continue to press it through the other hole. Drill the holes (of the Z-Stage Motor Mount) for the dowel pin to be slightly larger than 1/8 inches (3.2 mm) in diameter if the dowel rod will not fit through them.
   v. Remove the 6 \( \times \) 1 connector housing from the motor and place the six wires through the wire channel as shown in Fig. 4.
   vi. Reattach the wires to the connector housing, maintaining their previous color order: red, black, green, blue, yellow, and white.

5.17. Placing the \( \theta \)-stage and servo motor wires

(a) Previously made parts required: XZ\( \psi \)-Stage.
(b) Components required: 24-inch f-f pre-crimped wires [PL3] (15X, 2 gray, 2 purple, 2 orange, 2 yellow, 2 red, 2 black, 1 white, 1 blue, and 1 green), 1 \( \times \) 2 pin connector housing [PL10] (6X), 1 \( \times \) 4 pin connector housing [PL9] (2X), 1 \( \times \) 6 pin connector housing [PL8] (2X), heat shrink tubing [AZ8], and braided sleeving [AZ7].
(c) Instructions:
   i. Cut an approximately 16 inch (41 cm) length of braided sleeving.
   ii. Place 2 grey wires into a 1 \( \times \) 2 pin connector housing. Do not add a connector to the other side of the wires. Repeat for the 2 purple and 2 orange wires.
   iii. Create 2 1 \( \times \) 3 pin connector housings by using a flush cutter to remove one position from each of the 1 \( \times \) 4 connector housings.
   iv. Place 3 wires in a 1 \( \times \) 3 pin connector housing in the following order: black, red, and yellow. Do not add a connector to the other side of the wires.
   v. Place 6 wires into a 1 \( \times \) 6 pin connector housing in the following order: red, black, green, blue, yellow, and white. Do not add a connector to the other side of the wires.
   vi. The channel for this bundle of wires is shown and labeled in Fig. 4. Starting from the side with the Rotating Drum, push the wires (ends without connectors first) through the XZ\( \psi \)-Stage.
vii. When all of the wires are through the XZψ-Stage, place the braided sleeving over the bundle of wires. Position the braided sleeving such that there is approximately 1.5 inches (3.8 cm) of wire exposed on the end of the wire without the connector housings.

viii. Place 2 pieces of heat shrink tubing over the braided sleeving. Place them over the ends of the braided sleeving.

ix. Place the connector housings onto the wires. Using the continuity checker of a multimeter, make sure you do not mix the wires having the same color (black, red, and yellow).

x. With a heat gun, heat the heat shrink tubing to prevent the ends of the braided sleeving from fraying. Do not heat the 3D-printed components with the heat gun.

5.18. The Z-stage motor controller

(a) Previously made parts required: Z-Stage Motor Controller, assembled and programmed using the instructions in Section 5.2.

(b) Printed parts required: Rotating Electronics Drum [D23].

(c) Components required: #4-40 by 5/16 inch button heads screws [F17] (2X), 1 × 2 pin connector housings [PL10] (2X), 1 × 4 pin connector housings [PL9] (4X), 1 × 6 pin connector housings [PL8] (2X), six-inch male–female (m-f) pre-crimped jumper wires [PL7] (8X, 2 purple, and 1 red, black, green, blue, white, and yellow), and six-inch f-f pre-crimped jumper wires [PL1] (6X, 2 white, and 1 red, black, blue, and yellow).

(d) Instructions:

i. Create the Z-Motor cable by placing six male-female jumpers into the 6×1 connector housings in the follow order: red, black, green, blue, yellow, and white.

ii. Create the bus cable by placing four female-female jumpers into the 4×1 connector housings in the following order: red, black, yellow, and blue.

iii. Create the two limit switch cables by placing the two purple and two white wires into the 2×1 connector housings.

iv. Fasten the PCB into the Rotating Electronics Drum, noting the position as shown in Fig. 22.

v. Connect the cables as shown in Fig. 22. The white cable connects to the limit switch one (labeled “Lim1” on the PCB) and is routed through a hole going through the PCB and Rotating Electronics Drum. The purple cable connects to limit switch two (labeled “Lim2” on the PCB). The bus cable connects to the PCB as shown, such that its red wire is farther from the microcontroller. The motor cable connects as shown, such that the its red wire is closer to a set of four flyback diodes that protect the motor driver.

5.19. The ϑ-stage motor controller

(a) Previously made parts required: The mounted/wired Z-Stage Electronics and the ϑ-stage motor controller PCB, assembled and programmed as per Section 5.2.

(b) Printed parts required: Controller Shelf [D24].
Components required: #4-40 by 5/16 inch button heads screws [F17] (4X).

Instructions:
(i) Use the two #4 screws to fasten the Controller Shelf into the Rotating Electronics Drum.
(ii) Use two screws to fasten the θ-Stage PCB onto the controller shelf. The cables connected to the Z-stage PCB should go on the outside of the θ-Stage PCB, which will need to push on the cables to fit.
(iii) Connect the bus cable from the Z-Stage PCB to the θ-Stage PCB.

5.20. Electrical connections between rotating electronics drum and rotating bus connector

(a) Previously made parts required: The main carriage assembly and the Rotating Electronics Drum with the Z and θ motor controllers.
(b) Components required: 18-inch length of square tubing [M14] and 12-inch long circular tubes [M16] (2X).
(c) Instructions:
(i) Cut an 18-inch length of square tubing and place it through the main carriage assembly. Be careful to not remove the tubing from the main carriage for the remainder of the build.
(ii) Cut two 12-inch lengths of circular tubing.
(iii) Press fit the two circular tubes into the two holes (for passing the monofilaments of the θ-Stage) in the Rotating Bus Connector.
(iv) Slide the Rotating Electronics Drum onto the square tubing, rotating the assembly such that the two circular tubes pass through the PCB boards. Relative to the main carriage, there are two possible orientations of the Rotating Electronics Drum. Before making the wiring connections, make sure the 6 mounting holes align. They are on the outside of the Rotating Electronics Drum and the Rotating Bus Connector.
(v) There are seven wiring connections to make. Figs. 23 and 24 indicate these connections.
   A. Connect the purple cables together.
   B. Connect the Z-Stage Connectors together. The Z-Stage connector on the motor does not pass through the ψ-Stage in the bundle of wires, which makes it easier to identify.
   C. Connect the cables the pass through the ψ-Stage in the bundle. The bus, gray cable, orange cable, θ motor cable, and servo motor cable connect to the θ-Stage PCB as indicated by Fig. 23.

5.21. Fastening the rotating electronics drum and adding a Z-stage limit switch

(a) Printed parts required: Z-Stage Limit Switch Mount [D25].
(b) Components required: Limit switch [PL18], 1 x 2 pin connector housing [PL10], 3-inch m-m pre-crimped jumper wire [PL5], #2-56 by 3/8 inch screws [F2] (6X), #1–72 by 1/2 inch screws [F1] (2X), #1 washers [F7], and #4-40 by 5/16 inch button heads screws [F17] (4X).
(c) Instructions:
(i) Carefully slide the Rotating Electronics Drum toward the Rotating Bus Connector while manually adjusting the position of the cables such that they remain under minimal strain.
(ii) Use six #2-56 by 3/8 inch screws to fasten the drum in place.

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![Fig. 23. Mounting the θ-Stage electronics into the rotating electronics drum. The asterisks indicate the location of the red wire in each cable.](image-url)
iii. To wire the Z-stage limit switch, cut the 3-inch wire in half, and soldier the two wires to the “NO” and “C” pins of the switch, and place the crimps into the connector housing.

iv. Using the two #1 screws and washers, fasten the limit switch onto the Z-Stage Limit Switch Mount as shown in Fig. 25.

v. Connect the two cables with white wires and place as much of the connected cable into the drum as possible.

vi. Using the two #4-40 by 5/16 inch button heads screws, mount the Z-Stage Limit Switch Mount onto the drum as shown in Fig. 25.

5.22. Attaching the head of the fish

(a) Printed parts required: Fish Head [D26], Hinge Joint Top [D27], Hinge Joint Bottom [D28], Upper Coupler [D29], and Lower Coupler [D30]. The Upper Coupler and Lower Coupler should be fabricated from flexible filament [AZ2].

(b) Components required: Three-foot f-f pre-crimped jumper wires [PL4] (3X, one red, black, and white), 1 × 4 pin connector housings (2X), three-foot stainless steel circular tubing [M15] (not shown in Fig. 26), #2-56 by 3/8 inch set screws [F11] (3X), a #2-56 by 3/8 inch screw [F2], and a #2-56 by 5/8 inch screw [F10].
Note that in its current embodiment, the XYZ Fish includes a stainless steel tube through which wires are routed to power an actuated tail fin. If an actuated tail fin is not needed and the visibility of the tube is a concern, the stainless steel tube may be replaced by a clear acrylic rod (McMaster, Part No. 8531K13) cut to a length of approximately 30 inches (76 cm).

i. Using a fine hacksaw or rotary cutter, cut a length of approximately 30 inches (76 cm) from the stainless steel tubing.

ii. Press fit the cut end of the stainless tubing into the larger hole of the Upper Coupler. Starting from the bottom of the square tubing, use the stainless steel rod to press fit the Upper Coupler through the square tubing until it is flush with the top of the square tubing.

iii. Slide the Lower Coupler along the stainless steel tubing and press fit it into the square tubing, making sure the Lower Coupler is orientated such that it is able to depress the Z-Stage Limit Switch.

iv. Use a set screw to fix the position of the Lower Coupler relative to the stainless steel tubing.

v. Convert the 1\times4 pin connector housings into 1\times3 pin connector housings by removing one position from each using flush cutters.

vi. One at a time, slide each of the three pre-crimped jumper wires through the stainless steel tubing, and insert the top ends of the wires into a connector housing in the following order: black, red, and white.

vii. Slide the Hinge Joint Bottom into the Fish Head. The Hinge Joint Top has one hole for a #2-56 screw that goes fully through the part. This hole should line up with a slot in the Fish Head. If it doesn’t, reverse the orientation of the Hinge Joint Bottom.

viii. Fasten the Hinge Joint Top onto the Hinge Joint Bottom with the two #2-56 screws. The 5/8 inch screw should thread fully through the Hinge Joint Bottom and into the slot on the Fish Head.

ix. Slide the three wires though the holes on the Hinge Joint and into the Fish Head. Insert the wires into the other connector housing in the following order: black, red, and white.

x. Insert the stainless steel tubing into the Hinge Joint Top as shown in Fig. 26, and use the two #2-56 set screws to secure the stainless steel tubing relative to the Hinge Joint Top.

5.23. Completing the fish

(a) Printed parts required: Tail Fin [D32] and Fish Body [D31]. These parts should be made from flexible filament [AZ2].

(b) Components required: Waterproof servo motor [AZ5], #2-56 by 1/2 inch screws [F9] (4X), M3 by 8 mm screw [F21], 1 \times 4 terminal pins [PL9] (2X), five-foot lengths of monofilament [AZ6] (2X), and heat shrink tubing [AZ8].

(c) Instructions:

i. Cut the flanges on the waterproof servo, enabling it to press fit into the Fish Body.

ii. Remove the connector housing from the servo wires, and route the wires through a hole at the base of the servo pocket. Reconnect the connector housing, maintaining the color order of the wires (black, red, and white).

iii. Press fit the waterproof servo into the Fish Body, as shown in Fig. 27.
iv. Fasten the Tail Fin into the servo motor using the M3 screw, which should self-thread into the servo. Be careful to not over-tighten the screw.

v. Create a short three-pin male-male adapter by soldering the two 3x1 pin terminals together and heat shrinking the result. Use the adapter to connect the servo wires to the wires coming out of the stainless steel tubing. Encapsulate this electrical connection with a waterproof sealant (McMaster, Part No. 75825A5).

vi. Pass the lengths of monofilament through the Fish Head using the small holes located near the hinge joint. On each length of monofilament, tie a knot that is large enough to prevent the monofilament from being pulled out of the Fish Head.

vii. Use the four #2-56 by 1/2 inch screws to fasten the Fish Body to the Fish Head.

viii. Push the lengths of monofilament through the Rotating Electronics Drum and out through the top of the $\psi$-Stage, using the circular tubing inserted in Step 5.20. The monofilament nearest the Tail Fin needs to go through the tubing as shown in Fig. 27. If it does not, loosen the set screws on the Hinge Joint, rotate the Hinge Joint 180 degrees, and retighten the set screws.

5.24. $\theta$-Stage

(a) Printed parts required: $\theta$-Stage Pulley [D33], Z-Stage Limit Switch Extender [D34], and $\theta$-Stage Motor Mount [D35].

(b) Components required: Micro Metal Gearmotor [PL11], Gearmotor Bracket (comes with #2-56 nuts) [PL12], Magnetic Encoder [PL13], three-inch m-m pre-crimped jumper wires [PL5] (3X, one orange, gray, and purple), one-inch m-m pre-crimped jumper wires [PL6] (6X, one red, black, blue, yellow, white, and green), 1x6 pin connector housing [PL10] (3X), limit switches [PL18] (2X), limit switch [PL17], #1–72 by 1/2 inch screws [F1] (4X), #1 washers [F7] (4X), #2-56 by 1/4 inch screws [F8] (2X), #2-56 by 1/2 inch screws [F9] (2X), #2-56 by 3/8 inch screw [F2], #2-56 by 7/8 inch screws [F5] (2X), #2 washers [F6] (6X), heat shrink tubing, and a #2-56 low profile nut [F4].

(c) Instructions:

i. Install the magnetic encoder onto the micro metal gearmotor, following directions available from the supplier.

ii. Solder the one-inch pre-crimped jumpers wires into the encoder PCB as shown in Fig. 28, noting the color order: red, black, blue, yellow, white, green. Place heat shrink tubing on at least every other jumper wire.

iii. Place the six motor wires into the 6x1 pin connector housing, noting the different color order: red, black, green, blue, yellow, and white.

iv. Wiring the limit switches: cut the 3-inch wires in half, and solder the wires to the “NO” and “C” pins of each switch. The purple wires should be soldered to the largest of the three limit switches. Finish by placing the crimps into the connector housing.

v. Using the #1 screws and washers, fasten the two small limit switches onto the $\theta$-Stage Motor Mount as shown in Fig. 28, noting that the switch with orange wires is farther from the Z-Stage Limit Switch Extender.

vi. Slide the Z-Stage Limit Switch Extender into the Z-Stage Motor Mount. Using two #2-56 by 1/2 inch screws and two #2 washers, fasten the larger limit switch onto the Z-Stage Motor Mount as shown in Fig. 28.
vii. Use two #2-56 by 1 inch screws, two #2 washers, the gearmotor bracket, and the #2-56 nuts that come with the bracket to mount the micro metal gearmotor to the Z-Stage Motor Mount.

viii. The pulley's rotation relative to the motor shaft is fixed by a #2-56 screw that threads through a low profile nut and abuts the flat of the shaft. Embed the low profile #2-56 nut into a hexagonal pocket in the \( \theta \)-Stage Pulley. The recommended way to do this is to pull the nut into the pocket with the screw.

ix. Press-fit the pulley onto the motor shaft such that the end of the motor shaft is flush with the pulley. Use the #2-56 by 3/8 screw as a set screw against the flat of the motor shaft.

x. Partially thread the two #2-56 by 1/4 inch screws (with one #2 washer each) onto the pulley. These will be used in the next step for attaching the monofilaments.

5.25. Securing the Monofilaments of the \( \theta \)-Stage

(a) Instructions:

i. Place the \( \theta \)-Stage on the square tubing such the Z-Stage Limit Switch Extender would abut the \( \psi \)-Stage as shown in Fig. 29.

ii. Secure the monofilaments by wrapping them at least once around the pulley, routing them through the slots on the edge of the pulley, and then trapping them under the washers by tightening the #2-56 screws. The depression of the

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Fig. 28. Parts for and result of building \( \theta \)-Stage.

Fig. 29. Mounting the \( \theta \)-Stage and securing the monofilaments.
limit switch with the orange wires should coincide with the maximum desired upward angle of the fish, as shown in Fig. 29. To achieve this, manually rotate the pulley until the limit switch (orange wires) is depressed and then secure the wire that increases the fish’s angle as its tension is increased.

iii. Finish by securing the other length of monofilament.

5.26. Finishing the X-axis

(a) Printed parts required: X-Belt Holder Tops [D36 and D36m] and X-Belt Holder Bottoms [D37 and D37m].
(b) Components required: Three-foot 3/8 inch diameter stainless steel shafts [M10] (2X), four-foot long timing belt [M5], #4-40 by 1 inch bolts [F12] (8X), and #4 washers [F14] (8X).
(c) Instructions:
   i. If they are attached, remove the X-Stage Shaft Fixtures from the two Y-Stage Carriages.
   ii. If necessary, clean and decrease the stainless steel shafts.
   iii. Carefully insert the stainless steel shafts through the linear bearing mounted on the main carriage assembly.
   iv. Using the fasteners and washers, fasten the X-Belt Holder Tops and X-Bolt Holder Bottoms onto the ends of the stainless steel rods in the orientation shown in Fig. 30. Note that although there are hexagonal pockets for #4-40 nuts on the X-Belt Holder bottoms, the fasteners should self-thread into these components.
   v. Attach one end of the timing belt to an X-Belt Holder. To attach the timing belt to an X-Belt Holder:
      A. Pinch a loop of the belt together, meshing the belt teeth
      B. Push the pinched loop through a slot on the X-Belt Holder (towards the post)
      C. Press the loop and belt downward such that the loop is around the post
      D. Pull the belt away from the slot to tighten the loop onto the post
   vi. Take the loose end of the timing belt and route it though the idler pulleys and X-Belt Pulley as shown in Fig. 30.
   vii. Attach the loose end of the timing belt to the other X-Belt Holder.
   viii. Adjust the belt tension by loosening either X-Belt Holder and repositioning it. The belt should be just tight enough to prevent it from slipping relative to the X-Stage pulley.
   ix. Note that the X-Belt Holders should depress the Y-Stage limits switches at the extremes of the desired Y-Stage motion.
   x. Two optional components may be printed from PLA [AZ1] to make the range of the X-Stage easily adjusted. They are the X-Limit Bottom [D46] and X-Limit Top [D47] files, and two of each should be printed. They are designed to clamp (with #4-40 by 1 inch screws) on the stainless steel shafts supporting the X-Stage.

5.27. X, Y, and ψ-stage motor controllers

(a) Previously made parts required: Assembled Motor Controller Board (4X). The boards should be pre-programmed as per Section 5.2 as appropriate for each axis.
(b) Printed parts required: Electronics Case [D38] (4X), Electronics Cover [D39] (4X), X and ψ-Stage Electronics Mount [D40], and Electronics Cover Cap [D41] (3X).

(c) Components required: #4-40 by 1 inch screws [F12] (2X), #4-40 nuts [F15] (2X), #4-40 by 5/16 button head screws [F17] (8X), 1x6 pin right-angle header pins [PL8] (4X), 1 × 4 pin right-angle header pins [PL9] (8X), and 1 × 2 pin right-angle header pins [PL10] (8X).

(d) Instructions:
  
i. For each of the four Motor Controller Boards, solder the header pins as shown in Fig. 31.
  
ii. Mount each circuit into an Electronic Case using two of the four mounting holes adjacent to the motor driver.
  
iii. Place the Electronics Covers onto the Electronics Cases such that their rectangular cutouts are over the LEDs on the Motor Controller Boards. Fasten the covers in place using the #4-40 by 3/8 inch screws (two screws per cover is sufficient).
  
iv. The X-Stage Carriage has three mounting holes located on the same side of the carriage as the ψ-Stage limit switch. Press-fit the two #4-40 nuts into the two hexagonal pockets furthest from the limit switch. Using the #4-40 by 1 inch screws, fasten the X and ψ-Stage Electronics Mount onto the X-Stage Carriage such that the square post is as far from the ψ-Stage as possible.
  
v. Mount two enclosed Motor Controller Boards onto the square post of the X and ψ-Stage Electronics Mount such that the header pins for the limit switches point upward and the Electronics Covers are as far from the X-Stage Carriage as possible.
  
vi. Prevent the enclosed Motor Controller Boards from sliding off of the post by using a #4-40 by 3/8 inch screw to fasten an Electronics Cover Cap to the end of the post.
  
vii. Mount the two remaining enclosed Motor Controller Boards onto the square posts of the Y-Stage Motor Mounts such that the Electronics Covers are above the Motor Controller Boards. The Motor Controller Boards should be oriented such that their 6-pin headers (for the geared DC motors) point in the direction of the closest corner of the aluminum frame and repeat instruction 5.27(d) vi twice.

5.28. Master electronics enclosure

(a) Previously made parts required: Motor Controller Board, assembled and pre-programmed as per Step 5.2.

(b) Printed parts required: Master Electronics Mount [D42], Master Electronics Case [D43], Electronics Cover Cap [D41], On/Off Switch Mount [D44], and Master Electronics Cover [D45].

(c) Components required: Banana-to-Banana Cables [SF4] (2X, 1 red and 1 black), Toggle Switch [SF1], 1 × 4 pin connector housings [PL9] (4X), 36 inch pre-crimped f-f jumper wires [PL4] (4X, one red, black, yellow, and blue), 12 inch pre-crimped f-f jumper wires [PL2] (4X, one red, black, yellow, and blue), zip ties (2X), tee nuts [OB7] (2X), M3 by 8 mm screws [F21] (2X), #4-40 by 5/16 inch screws [F17] (4X), #4-40 by 1/2 inch screw [F16], and #4-40 by 1 inch screws [F12] (4X).

(d) Instructions:
i. Fasten the Motor Controller Board to the Master Electronics Case using two #4-40 by 5/16 inch screws and the mounting holes adjacent to the motor driver.

ii. Cut the plugs off one end of the Banana-to-Banana cables and remove 5 mm of insulation from the cut ends.

iii. Press the cuts ends of the cables through the On/Off Switch Mount, as shown in Fig. 32, and tin both cut ends of the wire.

iv. Solder the red cable onto either tab of the toggle switch. Solder a separate length of red wire (same gauge as cable) onto the other tab of the toggle switch.

v. Pass the red and black cables through the Master Electronics Cover (align the 4 holes off the On/Off Switch Mount and the Master Electronics Cover to get the correct orientation of the Master Electronics Cover) and then connect them to the screw terminal as shown in Fig. 32. On the silkscreen layer of the PCB (see Fig. 9), the red cable must connect to the side labeled “Batt+” and the black cable must connect to the side labeled “Batt−.”

vi. Mount the toggle switch onto the On/Off Switch Mount using the hardware that comes with the switch. Use two zip ties to provide strain relief to the red and black cables by zip tying them together near the pass-through hole of the On/Off Switch Mount.

vii. Create two bus cables (one 12 inch and one 36 inch) using the connector housings and pre-crimped f-f jumper wires. The color order of the wires should be red, black, yellow, and blue.

viii. Insert the two I²C bus cables through the On/Off Switch Mount and connect them to the two sets of header pins on the PCB for the I²C bus. The red wires on the bus cable must align with the header pins labeled “5v” on the PCB.

ix. Fasten the On/Off Switch Mount and Master Electronics Cover to the Master Electronics Case using 4 #4-40 by 1 inch screws and washers.

tax. Attach the Master Electronics Mount to the aluminum extrusion of the left Y-Axis using the tee nuts and M3 screws.

5.29. Wiring

(a) Components required: 36-inch f-f pre-crimped jumper wires [PL4] (8X, at least one red, black, yellow, and blue), 12-inch f-f pre-crimped jumper wires [PL2] (4X), 6-inch f-f pre-crimped jumper wires [PL1] (10X, at least one red, black, yellow, and blue), 1 × 2 connector housings [PL10] (14X), and 1 × 4 connector housings [PL9] (4X).

(b) Instructions:

i. Bus Connections

A. Connect the bus cable from the rotating bus connection (see step 5.13) to a bus connector on the ψ-Stage motor controller.

B. Create one 6-inch f-f cable with four pre-crimped jumper wires and two 1 × 4 connector housings. The color order of the wires should match that of the bus: red, black, yellow, blue. Use this cable to connect the bus from the ψ-Stage to the X-Stage motor controller.
C. Create a 36-inch f-f cable with four pre-crimped jumper wires and two 1 × 4 connector housings. The color order of the wires should match that of the bus: red, black, yellow, blue. Use this cable to connect the bus from the X-Stage to the left Y-Stage motor controller.

D. Connect the 12-inch bus cable from the Master Electronics enclosure to the other bus connection on the left Y-Stage motor controller.

E. Connect the 36-inch bus cable from the Master Electronics enclosure to a bus connection on the right Y-Stage motor controller.

ii. X-stage wiring

A. Attach the 6 × 1 pin X-Stage Motor Connector to the X-Stage Motor Controller.

B. Create a 6-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect X-Stage Limit Switch 1 to the switch connection labeled “LIM1” on the PCB silkscreen.

C. Create a 12-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect X-Stage Limit Switch 2 to the switch connection labeled “LIM2” on the PCB silkscreen.

iii. Y-left stage wiring

A. Attach the 6 × 1 pin Y-Left Stage Motor Connector to the Y-Left Stage Motor Controller.

B. Create a 36-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect Y-Left Limit Switch 1 (see Fig. 33) to the switch connection labeled “LIM1” on the PCB silkscreen.

C. Create a 6-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect Y-Left Limit Switch 2 to the switch connection labeled “LIM2” on the PCB silkscreen.

iv. Y-right stage wiring

A. Attach the 6 × 1 pin Y-right Stage Motor Connector to the Y-Right Stage Motor Controller.

B. Create a 6-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect Y-Right Limit Switch 1 (see Fig. 33) to the switch connection labeled “LIM1” on the PCB silkscreen.

C. Create a 36-inch f-f cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect Y-Right Limit Switch 2 to the switch connection labeled “LIM2” on the PCB silkscreen.

v. Ψ-stage wiring

A. Attach the 6 × 1 pin Ψ-Stage motor connector to the Ψ-Stage Motor Controller.

B. Create a 12-inch female-female cable with two pre-crimped jumper wires and two 1 × 2 pin connector housings. Use this cable to connect Ψ-Stage Limit Switch 1 to the switch connection labeled “LIM1” on the PCB silkscreen.

C. Attach one side of the cable to the Ψ-Stage limit switch and the other to the Ψ-Stage Motor Controller. Use the limit switch connection labeled “LIM2” on the PCB silkscreen.

vi. Θ-stage and servo wiring

A. Create a 1 × 3 pin male-male adapter identical to the one made in step 5.23(c) v.

B. Use the adapter to connect the wires for the servo motor that actuates the tail fin, aligning the black and red wires. One side of the connection is the 3x1 cable attached to the servo motor and routed through the square tubing. The other side of this connection is the 3x1 cable within the bundle of wires coming from the Ψ-Stage.

Fig. 33. Wiring diagram.
C. Attach the remaining wires from bundle coming from the ψ-Stage to the wires on the θ-Stage according the number of pins and color order.

5.30. Power Supply

(a) Components Required: Banana-To-Spade adaptors [DK1], 12 V Power Supply [SF2], and Supply Cable [SF3].
(b) Instructions:
NOTE: The specified cable [SF3] is designed to plug into outlets (Type B) in North America.
i. Make certain the cable is not plugged into an outlet, and fasten the pre-crimped connectors into the L (black wire), N (white wire), and ground connection (green wire) terminals.
ii. Connect the black banana-to-spade adapter into one of the terminals labeled “–V”.
iii. Connect the red banana-to-spade adapter into one of the terminals labeled “+V”.
iv. Check that the toggle switch on the master electronics enclosure is in the “off” position.
v. Connect the banana cables from the master electronics enclosure to the power supply, matching red with red and black with black.
vi. Plug in the power supply.

6. Operating instructions

6.1. Software protocol

While the master microcontroller communicates with each axis using I²C communication, the master itself communicates with a PC using a USB serial connection in order to receive position, homing, enable and disable commands. When the machine is powered on initially, all incremental encoders on each axis will read zero counts, and the machine will maintain “zero” position with all axes enabled.

In its default state, the master waits for new commands from the Serial port. To change the desired position for the robot’s six axes, the PC must send an ASCII message with the following format:

\!
x(m),y(m),z(m),pitch(rad),yaw(rad),tail(deg)\n
The exclamation point signifies the beginning of the command message, and the carriage return and newline characters signify the end of the command. All values are parsed as floating-point numbers. Special commands for each axis are shown in Table 11. see Table 8.,

During the homing operation, the motors will move at a slow, closed-loop velocity until limit switch LIM1 on the axis is depressed. At this point, the axis microcontroller resets its zero position, and remains at the homed position until commanded otherwise. If a ‘disable’ command is received by an axis, no voltage will be sent to the motor until the ‘enable’ command is received. At this point, the axis control loop will be re-engaged and the axis will remain at its current position until commanded otherwise. The Graphical User Interface (GUI) Python code demonstrates the use of all of these special commands. Its operation is described below.

6.2. GUI operation

The software repository includes a GUI intended to facilitate testing and basic use cases for the XYZψθ-Fish. The code also provides a demonstration of the communication protocol between a PC and the master microcontroller. The GUI was written in Python using the Tkinter user interface library, and communicates with the master microcontroller over a USB serial connection. The layout of the user interface is shown in Fig. 34. To install and run the GUI, a functioning Python 2.7 installation including the Tkinter library, the Numpy library, the Matplotlib library, and the PySerial Library is required. The GUI can be started from the IDLE Python development environment, or by typing “Python Gantry_Control.py” in a python-enabled terminal.

The “Serial Port” and “Baud Rate” input windows allow the user to configure the connection to the master microcontroller. Port names vary with operating system, but the provided master microcontroller firmware requires a connection at 115200 baud.

Once the details of the serial port are set, the user can connect to the master microcontroller using the “Open Port” button, and disconnect when required using the “Close Port” button. The sliders for each axis control the command sent to the master for each axis, where a value of 1000 (maximum) represents the maximum command in meters reflected in the input boxes under the main plotting area of the user interface. The minimum command possible for each axis is 0 in the GUI.

| Command | Function          |
|---------|-------------------|
| –111.1  | Home this axis    |
| –222.2  | Disable this axis |
| –333.3  | Enable this axis  |
The interface also includes an “enable/disable” checkbox that can be used to control whether all axes are enabled or disabled, a “home” button that runs the homing protocol on all axes, and a live plotting window. Any axis except for the tail (which provides no feedback) can be selected for plotting from a drop-down menu.

Finally, the GUI provides basic functionality for playback of a pre-recorded path in text file format. The positional data are interpolated to the GUI’s timestep (0.01 s), and the required format is as follows:

```
time(s) X(m) Y(m) Z(m) Pitch(rad) Yaw(rad) tail(deg) \r \n```

Any whitespace character or characters can be used to separate the values, and newlines are required between each successive data point. A file picker is initiated by the “choose playback file” button. Once a file is selected, “Enable File Playback” will play the file from the beginning. While the playback is active, the button’s text changes to “Disable File Playback” and clicking it will disable the playback. A subsequent press will restart the playback from the beginning. An Example of a correctly formatted text file is included in the repository.

### 6.3. Safely checklist

Before operating the robot, especially for the first time, it is imperative to ensure that all safety features are operating properly, and that your configuration space (defined by the boundaries of the fish tank) is adjusted such that the robot’s end effector will not crash.

1. Adjust position of the stops on the X axis, and the position of the limit switch carriers on the Y axis. The stops and switch carriers should be adjusted such that the robot’s configuration space will not allow collisions between the fish end-effector and the fish tank walls at the extremes of motion and for any angle $\psi$.
2. Manually move each axis of the robot so that the fish is located in the approximate middle of the configuration space and no limit switches are depressed.
3. Connect the power supply to the Master microcontroller’s ground and the e-stop switch terminal, then turn the power supply on.
4. Toggle the e-stop switch to power the device.
5. Plug USB cable into master control board.
6. Open the gantry control GUI software.
7. Set the axis limits in the text input boxes of the GUI to reflect an area smaller than the physical capacity of the robot given its limit switch positions for safety.
8. Set the baud rate (115200) address of COM port.
9. Click the button labeled “Open Port.”
10. One-by-one, move each slider on the interface to check that the motors respond. Do not move the sliders to their maxima, since the robot is not homed yet.
11. Use the drop-down menu labeled “Axis to plot” to visually confirm the closed-loop control performance of each axis in real time.
12. Check the limit switches:
   (a) Use the sliders to move the end-effector into the middle of its configuration space.
   (b) To check the limit switches, manually depress each and move the appropriate slider on the GUI. The carriage should not be able to move towards the depressed limit switch, but should be able to move away.

Once the safety check has been completed, the robot is ready for operation. Home the robot using the “home” button on the GUI. Once homing is complete, the robot is ready to play a file as described in the preceding subsection.

7. Validation

Efforts to confirm the robot’s operation included tests examining motion platform accuracy as well as tests examining how live archer fish responded to the robot. These results are presented in Sections 7.1 and 7.2 respectively.

7.1. Robot Motion

To validate the robot in its intended operation as a stimulus for ethropotic experiments with fish, it is necessary to determine whether the gantry is able to replicate expected fish motion in an appropriate experimental setting. To achieve this, the robot was run through three tests:

1. a 10-min segment in which a recording of actual 3-dimensional fish motion provided positional commands for each axis of the robot while it was out of water,
2. a one-minute traversal of an elliptical path at a forward speed of 100 mm/s while the fish was out of water, and
3. a one-minute traversal of an elliptical path at a forward speed of 100 mm/s while the fish was submerged in a 20-gallon fish tank.

Positional errors were recorded for all segments. The procedure and results are detailed in the following subsections.

7.1.1. Procedure

Test #1 could only be run out of water due to space constraints in the validation tank located at Lafayette College, where the XYZ-Fish was built. Tests #2 and #3 were designed to investigate whether the robot’s tracking performance is sensitive to whether the lure is submerged.

To obtain a realistic profile of fish motion for use in validating the robot in test #1, video data in the form of two camera feeds were obtained from a tank containing three Banded Archer fish (Toxotes jaculatrix) at Villanova University in Villanova, Pennsylvania, USA. Fish husbandry and experimental protocols were approved by the Institutional Animal Care and Use Committee of Villanova University.

In gathering the data for test #1, the focal fish was allowed to acclimate to a swimming area of 35x13x6.5 inches for 24 h. Data collection was performed after the fish was confined in the swimming area for an additional acclimation period of 10 min. Data were recorded for 10 min. A layout of the experimental setup and the associated camera feeds is shown in Fig. 35. Video data were collected using the Robot Operating System (www.ros.org). The Logitech webcams used to collect video data were calibrated using OpenCV, and recorded images at a framerate of 30 Hz and a resolution of 1280x720 pixels.

To obtain the three-dimensional position of the fish as accurately as possible, and to avoid any artifacts in the data resulting from mis-identification of the fish by an algorithm, the fish was tracked manually frame-by-frame using a Python program written with the OpenCV library. After image coordinates were obtained for the fish in the top view, a simple background subtraction, contour identification, and ellipse fitting image processing pipeline provided fish heading angle for each video frame. Heading angle was stored as a text file. Once image coordinates of the fish in both top and side views were obtained for each video frame, OpenCV’s triangulatePoints() function was employed to resolve the fish’s location in 3D space given each camera’s intrinsic parameters, along with the extrinsic parameters of each camera, which were measured relative to the camera mount frame (shown in Fig. 35) using a tape measure.

Three dimensional position information and measured heading angle were filtered using a 3rd order Butterworth filter with a cutoff frequency of 1.5 Hz. Fish pitch angle was approximated using the arctan of the fish’s vertical speed divided...
by its in-plane speed, where speed was determined using a backwards-Euler approximation of the derivative of the fish’s position along each axis.

Because tail motion of the fish was not recorded, tail motion for the validation test was approximated by a sine wave whose frequency varied between 0 and 2 Hz, scaling linearly with the fish’s in-plane acceleration.

For tests #2 and #3, an elliptical path was created that maximised the fish’s motion in a 20-gallon fish tank. Fish height varied as a sine wave with position along the ellipse’s circumference. Pitch angle was clamped at a floor of 0 radians and a maximum of $p/4$ radians, but was otherwise computed as the arctangent of vertical speed divided by in-plane speed.

7.1.2. Results and discussion

The results of the validation for test #1 are shown in Fig. 36. Maximum and Root Mean Square values for each axis’s error are given in Table 12. The errors shown in Table 12 are well within the limitations of the computer vision system used to measure fish position and angle. This indicates that the robot platform is well-suited for replicating the motion of fish such as archer fish.

Tests #2 and #3, while not based on actual fish motion, were designed to determine whether the robot’s behavior differs significantly when the fish end-effector is submerged. Fig. 37 shows results for test #2, and Fig. 38 shows results for test #3. These results indicate that the robot’s performance in water was nearly identical to its performance out of water. Error statistics for tests #2 and #3 are shown in Tables 13 and 14 respectively. Positional errors were comparable whether the robot was in water or not. It should be noted that because of the elliptical path’s abrupt turns at the apex of the ellipse’s major axis, the yaw angle ($\psi$) error’s maximum values are quite high. This is to be expected, since the changes in angle at the extremes of the ellipse are quite demanding (See Figs. 37 and 38). The paths chosen for the wet/dry comparison in tests 2 and 3 involved much more aggressive changes in $\psi$ that were observed in test 1, which represented actual fish motion.

7.2. Fish-robot interaction

To investigate whether the platform poses any major challenges when used in a fish-robot interaction study, a series of preliminary tests was conducted in which a single banded archer fish swam together with the lure in a tank. A single series of 10-min exposures of the fish to the lure allowed for an initial investigation of what effects the lure’s most basic embodiment might have on fish behavior in future studies. Data were collected at Villanova University in accordance with the guidelines of Villanova’s Institutional Animal Care and Use Committee (IACUC).

It is important to note that even if a lure is suitable for use in fish-robot interaction studies, its mere presence in the tank may not necessarily influence fish behavior. As has been reported widely in the literature, e.g. in [20], the lure’s appearance and/or the particulars of its motion may influence how a fish reacts to it. Easy manipulation of these dynamic and aesthetic features is central to the design of the platform presented in this paper. However, it is important to determine whether the lure’s presence adversely affects fish behavior in ways that would make experimentation with the platform difficult or even impossible. The preliminary study described in this section was intended to quantify whether permanent features of the robot, such as the lure’s physical presence or the platform’s motor noise, drastically affect fish behavior.
7.2.1. Procedure

In all of the 10-min trials conducted, the robot and a single, naïve banded archer fish swam together in a 0.89 m × 0.3 m × 0.30 m fish tank. The same fish was used in all trials. The lure portion of the robot was submerged in the water with the gantry powered down for 24 h prior to the start of data collection to allow the fish to acclimate to the lure’s appearance.

A single video camera was used to track and record fish and robot position during the experiments. A screen shot from this camera’s view during one of the experimental conditions is shown in Fig. 39. While this means that 3-dimensional measurements of focal fish position were not available, all analyses were conducted using the same monocular projection parameters, making comparisons between tests feasible.

To look at the potential for changes in the fish’s behavior when exposed to the robot, the robot’s lure was kept plain white, with the same hinge-type tail as in Section 7.1. Because the lure portion of the robotic platform presented here is likely to take many different visual forms in future experiments, a simplistic embodiment was a natural choice for preliminary data collection, preserving only the overall shape of an archer fish.

The lure was presented to the live fish in several different conditions for 10 min each. Tests were run sequentially in the order shown in Table 15 with approximately 1 min in between. While this battery of tests does not have the statistical power to support strong conclusions about how much influence this embodiment of the lure has or could have on fish behavior generally, it does offer insight into what effects the platform’s presence and motion may have on fish behavior for a baseline condition.

Trials were grouped into four “conditions” for analysis based on the robot’s general state during the trial: “No Robot,” “Robot Off,” “Robot On,” and “Robot Moving.” The “pre-recorded path” the robot followed in Robot Moving trials was taken

Table 12
Error statistics for validation test #1 (in air, recorded path of actual archer fish).

| Axis | Maximum Error | RMS Error | Units |
|------|---------------|-----------|-------|
| X    | 0.0191        | 0.00278   | m     |
| Y    | 0.0061        | 0.000966  | m     |
| Z    | 0.0016        | 0.000164  | m     |
| θ    | 0.00375       | 0.00820   | rad   |
| ϕ    | 0.132         | 0.0107    | rad   |

Fig. 36. Commanded vs. actual robot motion (left) and positional errors (right) for validation test #1 (in air, recorded path of actual archer fish).
from prior recordings of solitary archer fish motion as in Section 7.1. For the No Robot trials, the XZ-stage was removed completely, meaning that there was no gantry above the tank. The "Small Sinusoidal XY Commands" referenced in the Robot Moving trials were chosen to cause the motor amplifiers on the gantry to make noise without resulting in perceptible motion of the lure.

Because only one fish was used in the study, temporal effects of the fish’s experience level with the robot in each condition is a concern. Therefore, the sequence of trials in Table 15 was selected to provide repeated reversals, hopefully reducing any effects of order on the fish’s behavior.

7.2.2. Data post-processing

To avoid confounds associated with false positives or false negatives in automatic computer vision-based fish detection, focal fish position and robot position were recorded frame-by-frame using manual tracking for all trials. Fish depth and longitudinal position were based on a monocular projection of the fish’s coordinates in pixel space to the front plane of the tank using a pinhole camera model. The coordinate system for fish position originated at the bottom left of the front plane of the swimming area in the tank. A backwards Euler approximation was used to calculate planar fish speed, which was filtered using a 5-point median filter and converted to units of body lengths per second (BL/s) using a fish body length of 10 cm.

Before statistical analyses were performed on metrics derived from longitudinal fish position, position data were downsampled to 1 measurement every 10 s. This was done to prevent the highly autocorrelated nature of fish position from artificially biasing inferential statistics. One measurement every 10 s allows for sufficient time in which the fish could make decisions to go to a different location and execute those decisions. This preserves the statistical independence of repeated measurements of the fish’s location. Then, the longitudinal positions were compared to the robot’s position for all trials in which the robot was present in the tank, and the Longitudinal Distance (LD) from the fish to the robot was calculated. For trials representing the No Robot condition, the position of the robot during Robot Off and Robot On trials was used as a stand-in for robot position. This allowed for comparisons of LD among trials representing all conditions. For trials in which the robot moved, the robot’s Longitudinal position was manually tracked and post-processed using the same procedure performed for the live fish. Camera-based measurements were used rather than the gantry’s built-in feedback for consistency in measuring distance.

To investigate effects of robot presence, robot noise, and robot motion on the focal fish’s preferential longitudinal distance from the robot, downsampled LD data from all No Robot trials were pooled to represent baseline fish behavior (n = 180).
Similarly, LD data from both Robot Off trials were pooled to examine effects the visual presence of the robot may have had on the fish without motor noise as a possible influence \((n = 86)\). LD data from Robot On trials were pooled to examine effects of motor noise while the robot was moving imperceptibly in 3D space \((n = 239)\). Finally, LD data from Robot Moving trials were pooled to represent possible effects of robot motion on focal fish behavior \((n = 238)\). Pooling all LD data from all trials resulted in a roughly normal distribution of LD with a mean of 0.29 m, or roughly 3 body lengths, a standard deviation of 0.0828 m, a kurtosis relative to a standard normal distribution of 0.256, and a skewness of -0.274. These values, along with all other all statistical analyses, were computed using MATLAB.

![Graphs showing commanded vs. actual motion and positional errors for validation test #3 (submerged, elliptical path).](image)

**Fig. 38.** Commanded vs. actual motion (left) and positional errors (right) for validation test #3 (submerged, elliptical path).

| Error statistics for validation test # 2 (in air, elliptical path). |
|---|
| **Axis** | **Max Error** | **RMS Error** | **Units** |
| X | 0.0043 | 0.00334 | m |
| Y | 0.00310 | 0.000666 | m |
| Z | 0.00380 | 0.000496 | m |
| θ | 0.0365 | 0.0113 | rad |
| ψ | 0.437 | 0.0342 | rad |

| Error statistics for validation test # 3 (submerged, elliptical path). |
|---|
| **Axis** | **Max Error** | **RMS Error** | **Units** |
| X | 0.00400 | 0.00342 | m |
| Y | 0.00310 | 0.000638 | m |
| Z | 0.00390 | 0.000472 | m |
| θ | 0.0400 | 0.00723 | rad |
| ψ | 0.449 | 0.0322 | rad |
To investigate what effects the robot may have had on the focal fish's activity level, fish planar speed data were pooled using the same grouping of 10-min trials as previously described for the LD analysis. The data sampling rate and image resolution resulted in a noise floor on planar fish speed of approximately 0.25BL/s. Therefore, the focal fish was considered to be "moving" any time its speed was above a threshold of 0.5BL/s, or twice the noise floor. Across all trials, the focal fish spent 3.56% of the time (roughly 277 s out of 7800 total recorded seconds) above this planar speed threshold. Anecdotally, the archer fish in this study spent most of its time drifting slowly or staying mostly still. Because of this, mean speeds were low. Specifically, the mean planar speed of the fish for all trials was approximately 0.057BL/s.

Therefore, the average duration of the fish's periods of swimming motion, or Excursion Time (ET), was used as a metric of fish activity level. For all trials, the duration of each of the focal fish's bouts of motion was recorded. While ET is only one possible way to quantify a fish's level of activity, changes in the duration of movements should correspond to increased or decreased activity overall. As an example, if the fish were agitated by the robot's presence, or if the fish schooled with (or fled from) a moving robot, one would expect the average duration of its swimming "excursions" to increase.

Using the speed data from each trial, ET was recorded by tracking the difference in time between when the fish's speed rose above the threshold for active swimming (0.5BL/s) to the time when its speed dropped below this threshold. Speed data were not downsampled, since ET measures for each trial are not time series data, and are thus not expected to be causally autocorrelated. However, the distribution of ET pooled across all conditions and trials showed a highly left-skewed distribution, with the peak of the distribution very close to 0 s. Because of this, and because of the wide range of ET exhibited by the fish, ET data were log-transformed using the natural log. The distribution of pooled log-transformed ET values from all trials and all conditions represented an approximately normal distribution with a mean of −2.20, a standard deviation of 0.978, a kurtosis relative to a normal distribution of 0.0778, and a skewness of 0.4482. Therefore, log-transformed ET was used in the Statistical tests performed in Section 7.2.3.

### Table 15

| Test | Condition | Description |
|------|-----------|-------------|
| 1    | No Robot  | No Robot Present |
| 2    | Robot On  | Robot Present, Small Sinusoidal XY Commands, Tail Moving |
| 3    | Robot Moving | Robot Following Pre-Recorded XYZ Path, Tail Moving |
| 4    | Robot Moving | Robot Following Pre-Recorded XYZ Path, Tail Moving |
| 5    | Robot On  | Robot Present, Small Sinusoidal XY Commands, Tail Moving |
| 6    | No Robot  | No Robot Present |
| 7    | Robot Off | Robot Present, Powered Off |
| 8    | Robot On  | Robot Present, Small Sinusoidal XY Commands, Tail Not Moving |
| 9    | Robot Moving | Robot Following Pre-Recorded XYZ Path, Tail Not Moving |
| 10   | Robot Moving | Robot Following Pre-Recorded XYZ Path, Tail Not Moving |
| 11   | Robot On  | Robot Present, Small Sinusoidal XY Commands, Tail Not Moving |
| 12   | Robot Off | Robot Present, Powered Off |
| 13   | No Robot  | No Robot Present |

To investigate what effects the robot may have had on the focal fish's activity level, fish planar speed data were pooled using the same grouping of 10-min trials as previously described for the LD analysis. The data sampling rate and image resolution resulted in a noise floor on planar fish speed of approximately 0.25BL/s. Therefore, the focal fish was considered to be "moving" any time its speed was above a threshold of 0.5BL/s, or twice the noise floor. Across all trials, the focal fish spent 3.56% of the time (roughly 277 s out of 7800 total recorded seconds) above this planar speed threshold. Anecdotally, the archer fish in this study spent most of its time drifting slowly or staying mostly still. Because of this, mean speeds were low. Specifically, the mean planar speed of the fish for all trials was approximately 0.057BL/s.

Therefore, the average duration of the fish's periods of swimming motion, or Excursion Time (ET), was used as a metric of fish activity level. For all trials, the duration of each of the focal fish's bouts of motion was recorded. While ET is only one possible way to quantify a fish's level of activity, changes in the duration of movements should correspond to increased or decreased activity overall. As an example, if the fish were agitated by the robot's presence, or if the fish schooled with (or fled from) a moving robot, one would expect the average duration of its swimming "excursions" to increase.

Using the speed data from each trial, ET was recorded by tracking the difference in time between when the fish's speed rose above the threshold for active swimming (0.5BL/s) to the time when its speed dropped below this threshold. Speed data were not downsampled, since ET measures for each trial are not time series data, and are thus not expected to be causally autocorrelated. However, the distribution of ET pooled across all conditions and trials showed a highly left-skewed distribution, with the peak of the distribution very close to 0 s. Because of this, and because of the wide range of ET exhibited by the fish, ET data were log-transformed using the natural log. The distribution of pooled log-transformed ET values from all trials and all conditions represented an approximately normal distribution with a mean of −2.20, a standard deviation of 0.978, a kurtosis relative to a normal distribution of 0.0778, and a skewness of 0.4482. Therefore, log-transformed ET was used in the Statistical tests performed in Section 7.2.3.

### 7.2.3. Results

A one-way Analysis of Variance (ANOVA) was run using MATLAB on fish longitudinal distance from robot, LD, to investigate whether robot condition had any statistically significant effects on the fish's distance from the lure. The ANOVA revealed a significant difference in group means \( F(3, 724) = 57.28, p < .001 \). The ANOVA results were followed by post hoc comparisons using Tukey's HSD tests. The fish's mean LD for the No Robot condition differed significantly from the Robot Off condition \( (p = .0012) \) and the Robot Moving condition \( (p < .001) \). LD for the Robot Off condition also varied significantly

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**Fig. 39.** Video frame during fish–robot interaction trial.
from the Robot On condition \((p < .001)\) and the Robot Moving condition \((p < .001)\). The Robot On condition also varied significantly from the Robot Moving condition \((p < .001)\).

Using the same groups previously defined, log-transformed ET was also subjected to statistical analysis to determine whether robot condition had significant effects on the fish’s activity level. The following sets of log-transformed ET for each condition were assembled: No Robot \((n = 403)\), Robot Off \((n = 118)\), Robot On \((n = 485)\), and Robot Moving \((n = 436)\).

A one-way ANOVA performed on log-transformed ET revealed a significant difference in means across condition \(F(3, 1438) = 12.24, p < .001\). The ANOVA results were followed by post hoc comparisons using Tukey’s HSD. The pairwise comparisons revealed that the mean of log-transformed ET for the Robot Moving condition was significantly different than all other conditions: No Robot \((p < .001)\), Robot Off \((p < .001)\), and Robot On \((p < .001)\). No other significant differences between conditions existed.

7.2.4. Discussion

Box-and-whisker plots for LD and log-transformed ET are shown in Fig. 40. Transforming the means of log(ET) back into seconds yields the geometric mean of ET for each condition. These means, along with arithmetic means of LD for each condition, are shown in Table 16.

Fig. 40a and the accompanying statistical analysis show that mean LD, or longitudinal distance from the robot, was significantly larger for the No Robot condition than for the Robot Off condition. Recall that LD for the No Robot condition was calculated using the position of the robot when it was stationary in the Robot Off and Robot On conditions. This seems to suggest that the robot’s presence was an attractive stimulus when considering fish preferential location in the tank. However, LD in the Robot On condition was not significantly different from the control, so it is unclear whether the robot was repulsive in this condition, or whether it was simply ignored. LD for the Robot Moving condition was significantly smaller than all others, again suggesting that the lure may have been an attractive stimulus when it is moving, even in the absence of aesthetic enhancements such as eyes or color.

There are several possible interpretations of why the lure did not serve as a significantly more attractive or repulsive stimulus in the Robot On condition than in the control. For example, one may wonder whether the gantry’s sound had an effect on the fish’s preferential distance from the robot. This is an especially intriguing hypothesis given the fact that the fish preferred to stay closer to the silent stationary lure in the Robot Off condition vs. the noisier lure in the Robot On condition. However, if this were the case, one would expect the Robot Moving condition to also show the same null or perhaps a repulsive effect. The fact that LD is smallest in the Robot Moving condition seems to suggest that for this fish, in this series of experiments, the lure’s motion was the dominant stimulus, and did seem to decrease the fish’s preferential distance from the lure. This suggests that the robotic platform presented in this study is capable of serving as an attractive stimulus in

![Fig. 40a](image-url)  
(a) Fish LD for all conditions.  
![Fig. 40b](image-url)  
(b) Log-transformed fish ET for all conditions.

Table 16  
Geometric means of ET and arithmetic means of LD for each condition.

| Condition          | No Robot | Robot Off | Robot On | Robot Moving |
|--------------------|----------|-----------|----------|--------------|
| Geometric mean of ET (s) | 0.107    | 0.085     | 0.101    | 0.140        |
| Arithmetic mean of LD (m)  | 0.314    | 0.278     | 0.323    | 0.240        |
fish–robot interaction studies with archer fish. It is possible, as was reported in [20], that changing the lure’s appearance and/or tail-beat frequency would modulate LD for the Robot On condition in either an attractive or repulsive way. However, these permutations are beyond the scope of the current exploratory analysis.

When considering the fish’s activity level as measured by average log-transformed ET, shown in Fig. 40b with back-transformed means presented in Table 16, the Robot Moving condition showed significantly longer periods of fish swimming activity than all others. While ET does not reveal the specific reason that the fish was more active when the robot was moving, it does suggest that the robot’s motion had some measurable effect on fish behavior. Many studies in the literature have gone farther using more sophisticated metrics to determine whether a robot was “leading” or perhaps “chasing” a focal fish. However, such analyses are outside the scope of the present work. What the differences in log-transformed ET do convey is that the fish seems to have longer bouts of swimming behavior when the robotic platform is moving the lure, which is consistent with the behavior that would be expected if the goal of a study was to measure or enhance fish–robot interaction.

Taken together, these results suggest that the presence of the robotic platform developed in this paper could be a useful attractive stimulus in a fish–robot experiment, despite the visual presence of the gantry and despite the inevitable noise associated with the gantry moving the lure. The results also suggest that a moving robot can yield a more active fish. These results support the conclusion that factors not intended to influence the fish’s behavior, such as motor noise, are secondary to factors that are likely to be manipulated in future experiments, such as the robot’s appearance or motion.

8. Conclusion

This paper presented a flexible, extensible design for a gantry-style robotic fish platform, the $XYZ\psi\theta$-Fish, that will allow researchers in eThorobotics to investigate fish–robot interaction in ways not possible using platforms currently available in the literature. The design is cost-effective, adaptable to a number of different fish species and configuration space (tank) sizes, and buildable without specialized tools other than a hobby-level, single-nozzle FDM printer. The design is completely open-source and all sources files are hosted by the OSF (https://osf.io/yz6x7) and available under the GPL-3.0 license.

This paper provided interested laboratories with a comprehensive set of instructions for building and operating the platform and the authors hope that its use will accelerate further developments in the field of eThorobotics, particularly with respect to the ways in which the gross motion of a lure may stimulate or influence the social behavior of fish.

Declaration of interest

No conflicts of interest exist.

Human and animal rights

Fish husbandry and experimental protocols were approved by the Institutional Animal Care and Use Committee of Villanova University.

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