

Willow Joystick

DESIGN RATIONALE

Overview

The Design Rationale is intended to provide designers and maker information about the design process and design decisions behind the development of the Willow Joystick, a low force magnetic joystick for users with low strength.





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Introduction

After developing the LipSync, an opportunity arose to take the magnetic gimbal system and develop it further to create a low force addition to the MMC joystick library.

The Willow is intended for users that find the existing joystick options in the MMC library too high force or require too large of a range of motion, and need a lower force, lower range of motion option.

The Willow would be useful for users with conditions that limit their strength and range of motion, such as Spinal Muscular Atrophy.

Requirements

The goals and requirements outlined here are to assess if a device would meet the needs of a user, and determine when a design is sufficient for release.

User Needs / Goals

G01	Requires low force to operate
G02	Compatibility with existing toppers
G03	Device should be ergonomic and not put strain on the user's wrist during use
G04	Device should have a physical range of motion comparable to LipSync or typical gaming thumbstick (e.g., ± 10 mm)
G05	Minimize device envelope.

Requirements

F01	With the default topper, the joystick must require 30 g or less of force to fully displace the joystick
F02	Linear range of the joystick must be between a minimum of ± 5 mm and a maximum of ± 20 mm.
F03	The device is operable in two operating modes: Joystick HID and Mouse HID.
F04	A secondary user must be able to switch between operating modes
F05	A Primary User should be able to switch between operating modes
F06	Device must give the user visual or auditory feedback on the current operating mode.
F07	A secondary user must be able to perform a neutral calibration of the joystick
F08	The primary user should be able to perform a neutral calibration of the joystick
F09	Device should have swappable toppers.
F10	Devices should have toppers that are swappable by a Secondary User.
F11	Device should utilize the Oak modular topper interface.
F12	Device must be mountable, either compatible with the OpenAT Joystick mounting adaptor or have a built in $\frac{1}{4}$ "-20 UNC thread
F13	Device must output USB HID directly OR be compatible with an existing interface (e.g., LipSync Hub, Forest Hub)
F14	Design must be smooth with no sharp edges
F15	When passively resting on a desk or flat surface, the device must not slide when a horizontally applied force equal to the operating force is applied to the joystick.



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F16	When passively resting on a flat surface, the device must not tip over when a horizontally applied force equal to the operating force is applied to the joystick in any direction.
F17	Device produced a proportional output through the range of motion.
F18	Device must provide two axes of output.
F19	Device must have an input deadzone.
F20	Device must be compatible with the XAC

Evaluation Criteria

NF01	If device is bumped, it should not send an input to the connected device
NF02	Design must adhere to intuitive operations
NF03	Hysteresis (how well the device returns to center)
NF04	Device should have an input deadzone that is adjustable by a Secondary User.
NF05	Device should have a sensitivity that is adjustable by a Secondary User.
NF06	Device should have a way to invert the axes by a Secondary User.
NF07	Device should be able to withstand a drop of 3 feet onto a hard surface
NF08	Device should function when mounted vertically or upside down

Constraints

C01	Design must use off the shelf or 3D printed parts
C02	Design must use 3D printed plastic for gimbal and enclosure
C03	Device must not use batteries
C04	Commercial components should be available from multiple sources
C05	The parts should be sourced from as few suppliers as possible to lower shipping costs
C06	Parts must be available in low quantities
C07	Parts must not be region specific
C08	Device must be safe for the user and disclaim any potential hazards such as magnets
C09	Device should be assembled with commonly available tools as volunteer made OpenAT
C10	Only use hardware found in the LipSync gimbal in the Willow gimbal
C11	The number of fastener types in the device should be minimized
C12	The Willow joystick must work on the same magnetic gimbal principal as the LipSync
C13	Assembly should not require high strength or torque
C14	Device should be shippable within a Canada Post flat rate shipping box.
C15	Device should cost less than the BoM cost for the LipSync 4

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Stakeholders

- MMC
- GAME Checkpoints
- Neil Squire Solutions
- AbleGamers
- Primary users
- Secondary users
- Makers

Description of Targeted User

The targeted user of the Willow Joystick is someone who has limited to full range of motion with their hands (or other body part used to control the joystick, such as the chin), but limited strength. This includes users with spinal muscular atrophy (SMA), arthritis, muscular dystrophy, and multiple sclerosis.

This includes users that would use a LipSync, but either do not want the sip and puff aspect, or do not want to control it with their mouths.

Research

Commercially Available Options

Options that can be purchased but not made by a maker.

Celtic Magic Feather

Title / Name of device	Feather Joystick
Link	https://www.celticmagic.org/feather
Author	Celtic Magic
Cost	600 GBP





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The Feather Joystick by Celtic Magic is a magnetic low force joystick and mouse with a sensitivity of 5 grams. The method of sensing/magnetic joystick mechanism is unknown. It comes in three different models, mouse, joystick, and game control mixer. It has an optional hand support system that allows the Feather and a variety of switches to be supported relative to a user's hand. It also has a variety of optional addons, such as a light bar for user feedback that mounts to a PC monitor.

Requirements Met	Requirements Unmet
G01, G06, G07 F01, F02, F03, F04, F09, F10, F12, F13, F14, F17, F20, F21, F22, F23 NF02 C03, C05, C08, C14	G02, G03, G04 F04, F05, F11 C01, C10, C12, C15

Useful Design Features

- Low usage force
- Adjustable force
- Swappable Toppers
- Adjustable configuration through app
- Works with adaptors and stands
- Button inputs

Mo-Vis Micro Joystick

Title / Name of device	Micro Joystick
Link	https://www.mo-vis.com/products/wheelchair-joysticks/micro-joystick
Author	Mo-Vis
Cost	\$3400 CAD

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The Micro Joystick is a joystick module that can be connected to a wheelchair to control the wheelchair functions. It is designed for users with reduced range of motion and muscle strength. The same mechanism is also used in the Mo-Vis HID Joystick.

Requirements Met	Requirements Unmet
G01, G05, G06, G07 F01, F02, F13, F14, F17, F18, F20 NF02 C03	G02, G03, G04 F09, F10, F11 C01, C02, C04, C05, C06, C10, C12

Useful Design Features

- Low force
- Small size
- Swapable toppers
- LED for user feedback

DIY / Maker-Friendly Options

Options that can be made by a maker.

Celtic Magic Dangle Joystick

Title	Dangle Joystick
Link	https://www.celticmagic.org/dangle
Author	Celtic Magic
License	OSHW Definition 1.0



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Cost	55 GBP
Test Build (Y/N)	No
Add to Library (Y/N)	No



The Dangle Joystick is a low force, inverted, magnetically centered joystick with an operating force of 10 grams. You can build your own Dangle for 55 pounds, or buy one prebuild for 190 pounds.

Requirements Met	Requirements Unmet
G01, G02, G03, G05, G06 F01, F02, F13, F14, F15, F20, F21, F22 NF02 C01, C02, C03, C04, C05, C06, C08, C09, C15	G04, G07 F03, F04, F05, F09, F10, F11 C10, C12

Useful Design Features

- Low force operation
- Integrated button
- Configuration adjustable via app
- Optional camera mount

<INCLUDE ANY DESIGN FEATURES OF THE DEVICE THAT COULD / SHOULD BE CONSIDERED IN THE DESIGN OF ANOTHER DEVICE>

Joystick Force and Range of Motion Comparison

Joystick	Operational Force	Range of Motion	
Celtic Magic Feather	5, 10, 15, 20 g	Up to +/- 6 Degrees	
Celtic Magic J1, J2, J3	60 or 20 g	Unknown	
Celtic Magic Dangle Joystick	10 g	+/-35 degrees	
Mo-Vis Micro Joystick	8 or 5 g	3 mm movement	
LINX 400 Compact Remote	81 g	Unknown	



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ASL Micro Extremity Control	18 g	Unknown	
LipSync	50 g	+/-10 degrees	10 mm
Oak Joystick	525 g	+/- 25 degrees	
Spruce Joystick	75 g	+/-30 degrees	
Birch Joystick	115 g	+/- 2mm	+/- 2 mm
Xbox One controller	57-86 g	+/- 23 degrees	

Research Summary

Existing low force joysticks are in the 20g or less range, with a wide range of angles. Most of the extreme low force joysticks are in the $\sim\pm 6$ degrees range, while the rest of the joysticks do not go past ± 35 degrees.

Ideation

Key Features

Output Architecture: Microcontroller vs Hub

Weighted Decision Table

Options

Standalone Device

The first option for the Willow joystick is a standalone, self-contained device. This version of the willow would have the microcontroller, magnetic gimbal, any user feedback or user inputs all within the same enclosure. This device would have between two and zero user inputs, with user feedback limited to a small number of LEDs or NeoPixels and potentially a buzzer.

LipSync Hub

The LipSync hub option involves using the LipSync hub as the brains, switch input, and feedback of the Willow joystick. The joystick unit itself would just contain the magnetic gimbal, and the joystick unit would connect to the hub via RJ11 cable, just like the LipSync joystick. This would require reprogramming of the LipSync hub to distinguish the Willow and the Joystick, as well as the addition of a Willow mode that works without the sip and puff mechanism.

Forest Hub

The Forest Hub option involves using the Forest Hub as the brains, switch input, and feedback of the Willow joystick. The joystick unit itself would just contain the magnetic gimbal, and the joystick unit would connect to the Hub via RJ11 cable. This would require the Forest Hub to be updated to recognize



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the Willow, as well as the ability to translate the magnetic field readings into joystick output, similar to the joystick on the analog out.

Custom Hub

The Custom Hub option involves creating an entirely new hub for use with the willow joystick. This hub would be used as the brains, switch input and user feedback of the willow joystick. The hub would need to be created from scratch, with all that that entails. This would add another project on par with the forest hub to the Willow project.

Criteria

CAD Design Effort

CAD Design Effort is the amount of engineering time required to perform the CAD design on the 3D printed parts

PCB Design Effort

PCB Design Effort is the amount of engineering time required to perform the PCB design

Ease of Assembly

Ease of assembly is a maker targeted metric. It measures the ease of assembling the complete Willow setup.

MMC Supplier Role

Measures how many stocked parts common to MMC devices that the Willow uses.

Modular Toppers

Measure of if the device has modular toppers

Ease of Independent Customizability

Customizability is a measure of how customizable the device is. This includes swappable toppers, adjustable sensitivity, calibrations, and other settings users can tweak to improve how the device works for them.

Integrated Second Joystick

Measures if the devices has an integrated second joystick.

Upkeep Effort

Upkeep effort is a measure of how much work Makers Making Change must do to keep the device in a working and functional state. A one and done device would be rated high, where something that works



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with multiple devices and as such would need to be tested and ensure compatibility with all rated devices every update would be rated lower.

Programming Effort

Programming Effort is the amount of engineering time required to create or adapt code to make the device functional.

Size

Size refers to the overall size of the setup, including the joystick unit itself, as well as any hubs or switches.

Setup

Setup is a measure of how complicated the setup of each device is. This is an aggregate of the number of components involved (joystick, hub, switches) that must be positioned and mounted, as well as the amount of restrictions on how the components must be mounted, i.e. if text on a display needs to be legible vs an LED lighting up.

User Training

User Training is a measure of how intuitive it is to use the device, and how much training is required to get the user up and running with the device.

Cost

Cost refers to the overall cost of the device setup, including any hub, PCBs, etc. A rating of 1 is an equivalent price to the LipSync, with each point worth ~\$15-\$20

Interactability

Interactability is a measure of how many different ways the user can interact with the device. This includes the joystick but is also a measure of how many switch inputs the device has.

Feedback

Feedback is a measure how much feedback the user gets from the device.

Weighted Decision Matrix – Device Architecture

Options	Weights	Standalone	LipSync Hub	Forest Hub	Custom Hub
CAD Design Effort	2	4	6	6	1
PCB Design Effort	1	5	10	10	3
Programming Effort	3	5	1	4	3
Ease of Assembly	2	7	6	4	6
MMC Supplier Role	1	6	8	7	4



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Upkeep Effort	1	8	4	5	7
Cost	5	7	3	4	4
Size	5	8	5	6	6
Setup	2	7	3	4	4
User Training	4	7	6	5	5
Modular Toppers	2	5	5	5	5
Ease of Independent Customizability	4	3	9	6	7
Interactability	1	4	8	7	7
User Feedback	4	3	8	6	6
Integrated Second Joystick	1	0	0	6	6
Analog Output	3	7	0	10	8
Total		232	200	233	214

The weights in this decision matrix were based on input from two designers.

Microcontroller Options

Criteria for microcontrollers:

Requirements

- Connect to the magnetic sensor via Stemma cable
- Provide user visual feedback
- Ability for user to interact with the microcontroller to change modes

Bonuses

- Minimize cost
- Minimize footprint
- Bluetooth
- Analog output for TRRS

Microcontroller	Cost	Footprint (mmxmm)	Stemma	Bluetooth	Analog Out	Other	Link
SAMD21 QT PY	\$7.50 USD	22x18	Yes	No	Yes		Link
RP2040 QT PY	\$9.95 USD	22x18	Yes	No	Yes	Dual core microcontroller	Link
CH552 QT PY	\$4.95 USD	22x18	Yes	No	Yes	Almost no Arduino support, compiles in C not C++ so most	Link



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						libraries don't work	
Seeed XIAO nrf52	\$9.90 USD	22x18	No	Yes	Yes		Link
CH32V203 QTPY	\$4.95 USD	22x18	Yes	No	Unknown	Almost no Arduino support	Link
nRF52840 ItsyBitsy	\$19.95 USD	36x18mm	No	Yes	Yes		Link
nRF52840 glasses driver	\$24.95 USD	58x19	Yes	Yes	No	Has lots of unneeded sensors	Link
Metro Mini 328 V2	\$14.95 USD	44x18	Yes	No	Yes		Link
ESP32 Pico QTPy	\$14.95 USD	22x18	Yes	Yes	Yes	Also has Wi-Fi	Link

Microcontroller recommendation

If Bluetooth is not a requirement, the SAMD21 QTPY is the best choice for its low cost, small footprint, stemma and analog capabilities while not having any unneeded features such as extra sensors.

If Bluetooth is a requirement, the ESP32 Pico QTPY is the best choice for its small footprint, Bluetooth capabilities, analog output, stemma port while minimizing unnecessary features.

Microcontroller Pros

- Able to function as a standalone device
- Low cost

Microcontroller Cons

- To add capabilities beyond what is included with the microcontroller (More sensors or button inputs) either a stemma module or a protoboard and wires are required.
- Limited feedback abilities

Hub Options

Hub	Price	Inputs	Feedback	Adjustability	Output Modes
LipSync Hub	\$107.48	<ul style="list-style-type: none"> • 3x 3.5mm switch Jacks • RJ11 i2c connector • 2x onboard push buttons 	<ul style="list-style-type: none"> • Audio buzzer • 3x LEDs • Text display 	<ul style="list-style-type: none"> • Neutral reset • Extent calibration • Cursor speed adjustment 	<ul style="list-style-type: none"> • HID Gamepad • HID Mouse • Bluetooth • USB





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Forest Hub	\$78.54	<ul style="list-style-type: none"> • 5x 3.5mm switch Jacks • RJ11 i2c connector • 2x onboard push buttons • 3.5mm TRRS jack 	<ul style="list-style-type: none"> • Audio buzzer • 5x RGB LEDs 	<ul style="list-style-type: none"> • Neutral reset • Cursor speed adjustment 	<ul style="list-style-type: none"> • HID Gamepad • HID Mouse • USB
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To make the willow joystick work with the hubs, the hubs themselves would need a firmware update. The hubs would need the basic programming added to allow them to translate the readings from the magnetic sensor into the HID output. They would also need to have an addition that allows them to recognize when a willow joystick is connected. The forest hub would just need to check if the magnetic sensor is attached, but the LipSync hub would need to be able to tell the difference between a willow joystick and a LipSync joystick. The LipSync hub already has the firmware required to convert magnetic sensor readings into HID, although if the order of magnet and sensor is reversed a slightly different version would have to be used for the Willow.

After reviewing the firmware of both the Forest hub and the LipSync hub, the firmware of the LipSync is much more complicated than the firmware of the Forest, with the functions spread across 16 different files. To make the Willow compatible with the LipSync Hub, a member of the LipSync development team who is familiar with the code would be required to help with the coding process to keep the project on schedule.

Hub Pros

- Increased user feedback
- Integrated switch inputs
- Integrated neutral or extent calibration
 - Extent calibration more difficult with forest, text makes it easier
- Integrated cursor speed adjustment

Hub Cons

- Increased cost
- Joystick cannot be used as a standalone
- Chosen hub will need a software update to include the software needed for the Willow
- No possibility of TRRS output

When deciding on the output architecture, the deciding factor between standalone and hub architecture depends on the expected use case. If the Willow is intended to be used like the Birch, as just a joystick with switch access being provided by another device such as the XAC or the Rocket Switch interface, then the standalone microcontroller option provides enough functionality for the intended

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use case. However, if the Willow is intended to have integrated switches, extensive user feedback, and extent calibration, it makes more sense to make it a hub output device to save development time and money.

Neutral Calibration Options

- Microcontroller reboot/calibration on startup
- Externally triggered calibration

The two primary methods of neutral calibration are performing a calibration on microcontroller startup, and calibrating while the microcontroller is already powered on.

Calibration of the joystick during operation can be done by rebooting the microcontroller and taking advantage of the startup calibration. Most microcontrollers include a reboot button on the board itself, and the enclosure can be designed to allow a primary or secondary user to press the button to reboot the microcontroller and calibrate the neutral position.

Triggering the neutral calibration without rebooting the joystick would require an input to the microcontroller such as a button or switch jack or a movement pattern on the joystick such as holding it in a certain corner for a length of time then moving to another. If the microcontroller does not have an onboard button that is not connected to the reset pin, then an external button or jack would be needed to allow the user to trigger the reset. This button can either be directly wired to the microcontroller pins, or it can be connected a stemma button breakout board. This requires more parts, but works with accessible switches and preserves information between calibrations. A movement base calibration works without requiring additional hardware, but could be accidentally triggered by a user in the course of normal operation.

Extent Calibration Options

Out of all the joysticks and hubs available through Makers Making Change, only the LipSync has extent calibration. The birch mentions deadzone calibration via serial in the ReadMe, but this is absent from the User Guide and Maker Guide. Extents calibration reads the value at each corner of the joystick range, and uses that information to properly calibrate the output along the full range of joystick motion.

When discussing extent calibration with a GAME checkpoint leader, we were told that while extent calibration could be a useful tool for Occupational Therapists or other trained secondary users, it could prove detrimental if the primary user or an untrained user attempted to perform an extent calibration and incorrectly calibrated it.

When performing an extent calibration on the LipSync, the user follows the directions on the screen, holding the mouthpiece in the four corners until the LipSync beeps.

To perform this type of extent calibration, the LipSync needs an input to initiate the calibration, and feedback to inform the user when to move to each corner. The text display also allows the instructions to be displayed to the user in real time, instead of having to refer to a user guide. This is not necessary for an extents calibration, but it does greatly simplify the process.

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If using a hub, the extent calibration requirements are largely already met. The hubs have enough inputs that the user can use one to initiate an extents calibration, and both hubs have user feedback to time the different steps of the process. The LipSync Hub also has the text based display to show the steps in real time. The forest currently has no build in extent calibration, so that would need to be added via the same software update that adds Willow compatibility.

When using a microcontroller, the user feedback and input need to be provided. The options for providing input are the same as the options for a non reboot neutral calibration. If the microcontroller does not have an onboard input button, and external button or switch jack would be required. These can either be soldered directly to the microcontroller pads or connected via the stemma port. To provide user feedback, most microcontrollers from Adafruit have an LED, and some come with a NeoPixel LED that can be used to give feedback in any colour. Additional audio or visual feedback can be added by wiring to the microcontroller pins or added via stemma port.

Analog Output

HID Remapper

<https://github.com/jfedor2/hid-remapper>

The HID Remapper is a configurable device that allows the remapping of inputs from HID devices. There are currently 9 different form factors of the device, 8 custom boards and a prebuild microcontroller from Adafruit. The v7 board is designed for use with the XAC and the Sony Access Controller (SAC), and has four analog outputs that work with the XAC. The four analog outputs are intended to be used as two analog joysticks, and two analog trigger inputs.

The device is programmed and powered through the USB C port, the USB A ports on the top are for HID input, and the 3.5mm jacks are for outputs. In addition to the 4 analog outputs, there are also 10 3.5mm switch outputs.

This is currently the only version of the HID remapper that supports analog outputs.

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Figure 1: HID Remapper V7

Integrated Analog Output

An option for analogue outputs is to integrate them into the device itself. Including a 3.5mm TRRS jack in the device or associated hub allows two of the PWM ports of the microcontroller to be used to emulate the output of the potentiometers in an analog joystick. The voltage from the connected controller can be measured by an analog input pin to determine the expected output voltages for the different joystick positions.

Centering Strength Adjustment

There are two general methods available to change the centering force of the Willow gimbal

- Change the distance between the gimbal and sled magnet
- Change the strength of the sled magnet

For the sake of keeping the strength adjustment user friendly, making changes to the magnet in the gimbal itself will be disregarded, focusing on making changes to the magnet in the sled which is more accessible to the user.



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Changing the distance between the sled and gimbal allows for the strength to be changed without changing the magnet used. This can be done by using a screw to advance or retract the magnet, as well as having a variety of locations in the sled that the magnet can be mounted in. Mounting the magnet in different locations in the sled would require the sled to be opened and the magnet moved. Changing the position of the magnet using a screw allows for a secondary user to change the strength without opening the enclosure while allowing the strength to be adjusted anywhere between the two extremes.

Changing the strength of the sled magnet can be done in two ways. The first way that it can be done is changing the magnet used in the sled for a different magnet with a stronger field. The second method is to add more magnets. This does have diminishing returns as the number of magnets increases. The following is an excerpt from the LipSync Design rationale when exploring this option for the LipSync Gimbal

“When stacking magnets, the magnetic force increases until the thickness of the stack reaches the diameter of the magnets [first4magnets.com]. Since the magnets used in the LipSync are 2.5mm x 8mm, 3 to 4 can be stacked before reaching diminishing returns. This is demonstrated in a graph showing the force vs thickness of the magnet. Note the X axis does not increase linearly. [totalelement.com]

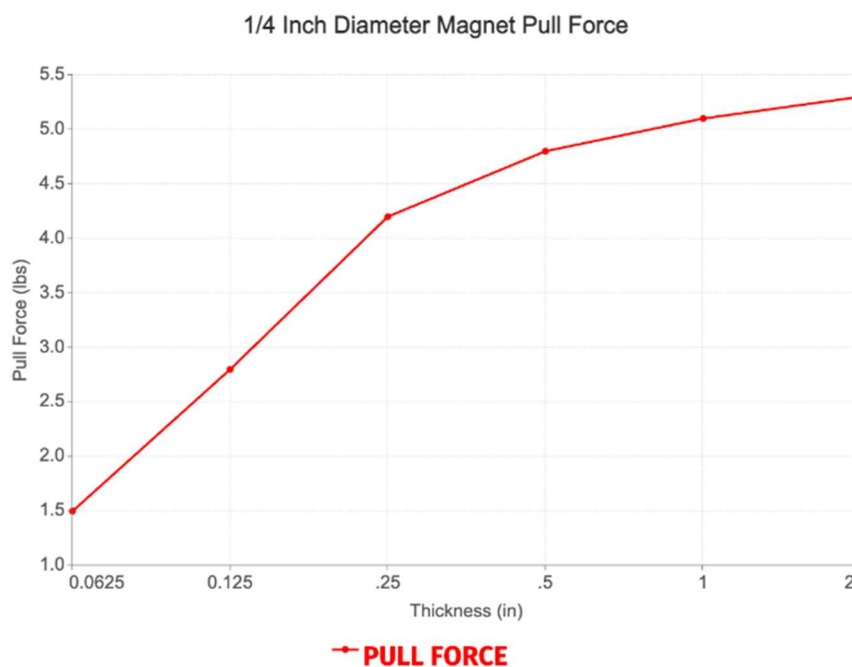


Figure 2. Magnetic Force with Greater Thickness.

“

Pros and Cons of Different Mounting Methods

Method	Pros	Cons
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Different mounting locations	<ul style="list-style-type: none"> Only uses one magnet 	<ul style="list-style-type: none"> Requires disassembling and reassembling the sled The need to support the magnet makes the number of possible places very small
Variable mounting location (screw)	<ul style="list-style-type: none"> Adjustable over the entire range with no defined stops Only requires one magnet 	<ul style="list-style-type: none"> The rotation of the screw changes the location of the magnet slightly, requiring a recalibration
Stronger magnet	<ul style="list-style-type: none"> Only uses one magnet 	<ul style="list-style-type: none"> Requires all the magnets of different strengths have the same dimensions Need to take apart the sled to change magnets
Using more magnets	<ul style="list-style-type: none"> If the first magnet is secured, more can be stacked in behind it from the exterior of the enclosure to change strength without opening the enclosure 	<ul style="list-style-type: none"> Different steps of strength with no in-between Diminishing returns with more magnets, up to 3 or 4

Features of the LipSync Gimbal

The following is a list of all components of the LipSync gimbal, and a judgement of if they are required in the Willow joystick

Sled

- Centering magnet
 - Needed
- Sensing magnet
 - Needed, but could be moved to the gimbal
- Bearing seats
 - Needed
- Cable management
 - Needed
- Angle hard stops
 - Needed
- Sliding rails
 - Needed
- Arm tabs





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- Needed

Outer Gimbal

- Angle hard stops
 - Needed
- Cable management
 - Needed if the sensor stays on inner gimbal
- Part identifiers
 - Needed
- Bearing seats
 - Needed
- Bearing posts
 - Needed

Inner Gimbal

- Shield
 - Needed
- Luer adaptor
 - Unneeded
- Air path
 - Unneeded
- Pressure sensor
 - Unneeded
- Magnetic sensor
 - Needed, but could be moved to sled
- Centering magnet
 - Needed
- Angle hard stops
 - Needed
- Part identifiers
 - Needed
- Bolt holes
 - Needed, but only if magnetic sensor stays on inner gimbal
- Cable management
 - Needed, but only if magnetic sensor stays on inner gimbal
- Bearing posts
 - Needed

Bare Minimum Changes

- Remove pressure sensor, air tube, and Luer lock
- Design topper base that fits in Luer compartment

Maximum Changes

- Move magnetic sensor to the sled





Willow Joystick

DESIGN RATIONALE

- Remove pressure sensor, air tube and Luer Lock
- Move sensor magnet to inner gimbal
- Shrink the gimbal to remove the space
- Redesign Luer lock compartment to allow swappable toppers

Topper Compatibilities

Oak

The Oak toppers all come in small, medium and large, and connect to the oak joystick via a collet system that clamps onto the stick of the oak joystick module. The toppers then screw onto the collet. The oak comes with 5 styles of topper.

- Ball
- Concave
- Convex
- Goalpost
- Stick

For this style of topper to work, it needs the joystick to have a stick that is identical to the stick found on the Oak joystick. A test would also have to be conducted to evaluate if the difference in hardness/friction between 3D printed plastic and the molded plastic of the Oak joystick affects the secureness of the collet connection. If the stick on the willow is 3D printed, it may be possible to print it directly with the thread used on the collet and bypass those parts entirely.

Pros

- Extremely secure connection
- Large variety of compatible toppers

Cons

- Collet is difficult to print and fragile, with layer lines
- Many parts required to attach the topper to the joystick
- Several toppers may be too heavy for use with a low force mechanism

Mass of Oak Toppers

Style	Small	Medium	Large
Ball	11g	18g	29g
Concave	10g	15g	14g
Convex	4g	9g	10g
Goalpost	14g	17g	19g
Stick	34g	50g	67g



Willow Joystick

DESIGN RATIONALE

Birch

The Birch toppers connect to the joystick by a friction press fit on the joystick module. They are designed for the sliding motion of the Birch joystick, and not the rotating motion of a traditional joystick. The birch comes with 5 different styles of topper.

- Concave
- Large Dome
- Medium Dome
- Ring
- Small Dome

To make these work with the willow gimbal, the profile of the willow gimbal stick needs to match that of the Birch joystick.

Pros

- Simple design
- Minimal parts required to make the topper fit to the joystick

Cons

- Individual tolerances between printers can make press fit difficult
- Press fit may not work on the 3d printed plastic version of the Birch topper

Mass of Birch Toppers

Topper	Mass (g)
Concave	1.0
Large Dome	4.9
Medium Dome	1.7
Ring	1.5
Small Dome	0.6

Evaluation Criteria

The primary criteria that toppers will be evaluated on are attachment and weight. Attachment is a measure of how well the topper attaches to the joystick stick. Weight is a measure of how much each topper weighs.

Since both sets of toppers were originally designed for different joysticks, it is entirely possible that both are unfit for the use case of the Willow.





Willow Joystick

DESIGN RATIONALE

The oak toppers have a large variety in their weights, ranging from 4 to 67 grams. This number does not include the weight of the collet and the topper nut, which weight 1.04 and 4.64 grams respectively. The current requirement for the centering force of the Willow is 30 grams or less. Since the weight of the topper is not applied perpendicular to the stick and the effective moment arm is the length of the topper multiplied by the sine of the angular displacement, it is possible to have a heavier topper than the max displacement force of the joystick. However, the heavier the topper, the lower the effective centering force, with the force getting lower the more it is displaced. If a compatible willow topper can be designed, either with a matching stick to the oak or with the correct thread that matches the topper nut, then the toppers with a mass of 15 grams or less could be trialed with the willow.

The Birch toppers are all below 5 grams in weight, with one being below 1 gram. They are designed for the Birch, which has a sliding motion, not a pivoting motion. The press fit has been known to have a tendency to pop off of the topper, especially the ring topper. While the Birch toppers are low weight enough to work with the willow, the lack of a secure attachment point makes them unsuitable for use with the willow.

Features Vs Costs

Feature	Cost	Benefits
Magnetic Gimbal	\$25.71	Joystick core
Switch Inputs	\$2.29/Switch Input	Allows the user switch inputs
LED Outputs	\$0.42/LED	Single colour on/off visual feedback
NeoPixel Outputs	\$1.47/NeoPixel, sold in 5 pack	Multicolour on/off visual feedback
Text Display	\$30.47	Text visual feedback
Audio Feedback	\$0.92	Musical note audio feedback
Tactile Buttons	\$1.02/Button	Built in device button inputs
Bluetooth	~\$5	Connect to devices without needing to plug into them

Options for Multiple Joysticks

Analog Input

A simple way of having multiple joystick inputs is to have analog TRRS joystick inputs, such as on the forest hub. This allows for analog joysticks such as the oak or spruce to be used alongside the Willow. However, the downside to this is the fact that the analog joysticks in the MMC library are all higher force than the Willow, which was developed to provide a low force alternative. Using analog joysticks in addition to the willow would be difficult for someone who requires the low force of the willow to be able to use a joystick.

Multiple i2c buses

Since the same magnetic sensor is used in the gimbal of every Willow Joystick, there is no way to differentiate them when they are on the same i2c bus. Using a multiplexer would allow for multiple of



Willow Joystick

DESIGN RATIONALE

the same sensors to be connected at the same time. However, the library used for the magnetic sensor does not have a method of verifying when a connection has been made, so verifying the number of joysticks attached to the central hub will be difficult and may rely on user input.

Multiple Complete Willows

The simplest option for using multiple joysticks is to simply use multiple independent joysticks instead of having a single central hub with multiple joysticks. This increases the overall cost of the setup significantly, but eliminates the design and usage challenges posed by the other methods.



Willow Joystick

DESIGN RATIONALE

Ideation Decisions

Idea	Decision (Abandon, Modify, Proceed)	Justification
Standalone Architecture	Abandon	Hub option chosen
Hub Architecture	Proceed	<ul style="list-style-type: none"> • Allows for reuse of LipSync code • Provides large amount of user feedback • Existing neutral and extent calibration • Makes the willow compatible with future hub reworks • Adds switch inputs • Allows the joystick unit to be as simple as possible



Willow Joystick

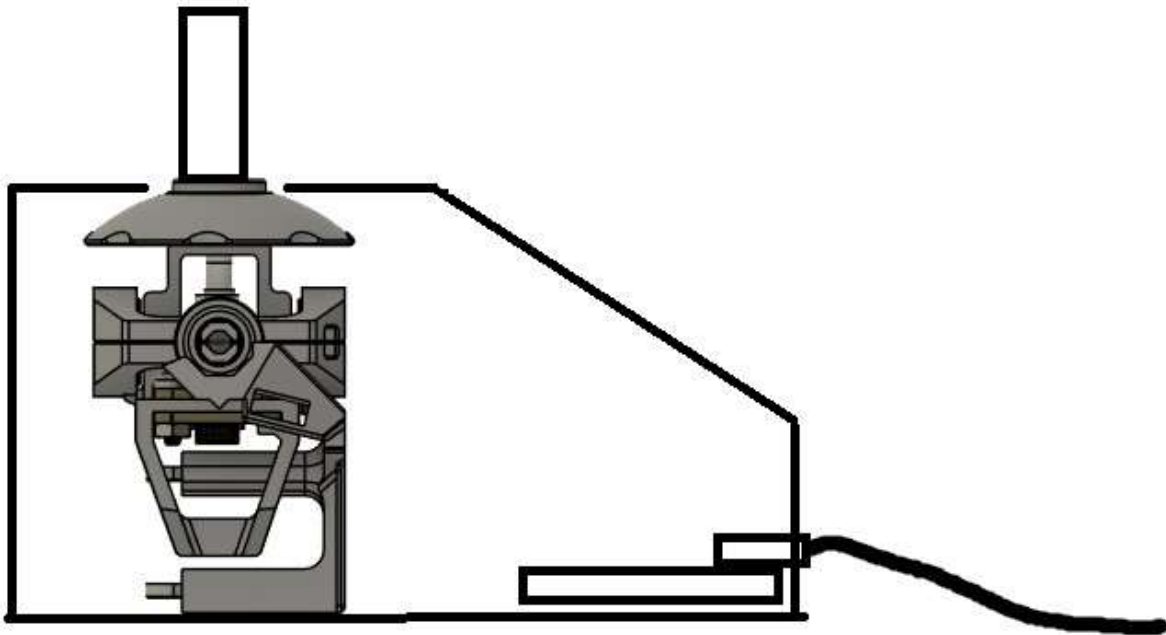
DESIGN RATIONALE

Conceptual Design

Gimbal Design

Concept 1: Existing LipSync Gimbal

A joystick made from an unchanged LipSync gimbal.



Physical Component / Enclosure

The gimbal used will be identical to the LipSync gimbal, but with the air path components not installed.

Electrical Components

In this version, both of the pressure sensors are removed, and the magnetic sensor is connected directly to the RJ11 jack.

Code Structure / Function

The software used is a version of the LipSync code that has been modified to have all pressure and sip/puff functions removed.

Willow Joystick

DESIGN RATIONALE

Concept 2: Redesigned Magnetic Gimbal

A gimbal based on the principals used in the LipSync gimbal, but redesigned to make it as short and compact as possible.



Physical Component / Enclosure

Willow Hub

The Willow Hub is a LipSync Hub that has been modified to replace the LipSync name with the Willow label.

Willow Joystick

The Willow joystick consists of two main components, the enclosure and the gimbal. The enclosure has a main base, which the gimbal sandwiches between, with the shell going overtop and securing everything in place. The gimbal is based off the LipSync gimbal, but compressed as much as possible to keep the profile of the Joystick low.

Electrical Components

Willow Hub

The Willow hub is electrically identical to the LipSync Hub.

Willow Joystick

The magnetic sensor is removed from the gimbal, and is instead mounted to the sled. This allows the extensive cable routing to be removed and the wiring simplified. The stemma cable from the magnetic sensor is directly connected to the RJ11 jack that is pinned in place in the enclosure.

Code Structure / Function

The software used is a version of the LipSync code that has been modified to have all pressure and sip/puff functions removed. Other minor changes have also been made, with one of the axis inverted and the deadzone expanded to account for the new sensor location and lower centering force.



Willow Joystick

DESIGN RATIONALE

Concept Decisions

Concept	Decision (Abandon, Modify, Proceed)	Justification
Existing LipSync Gimbal	Abandon	<ul style="list-style-type: none"> • High profile • Significant portions of the gimbal were designed around the airpath which is no longer needed
Redesigned Magnetic Gimbal	Proceed	<ul style="list-style-type: none"> • Lower profile makes it more comfortable to use • All the initial CAD had been already done as a personal project working on a standalone Bonsai Joystick

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Redesigned Magnetic Gimbal	Proceed	<ul style="list-style-type: none"> • Lower profile makes it more comfortable to use • All the initial CAD had been already done as a personal project working on a standalone Bonsai Joystick

Willow Joystick

DESIGN RATIONALE

Prototyping

Prototype 1: Redesigned Magnetic Gimbal

A gimbal based on the principals used in the LipSync gimbal, but redesigned to make it as short and compact as possible.



Physical Component / Enclosure

Willow Hub


The Willow Hub is a LipSync Hub that has been modified to replace the LipSync name with the Willow label.

https://github.com/makersmakingchange/LipSync/blob/main/Documentation/LipSync_BOM.csv

Willow Joystick

The Willow joystick consists of two main components, the enclosure and the gimbal. The enclosure has a main base, which the gimbal sandwiches between, with the shell going overtop and securing everything in place. The gimbal is based off the LipSync gimbal, but compressed as much as possible to keep the profile of the Joystick low.

Commercial Parts

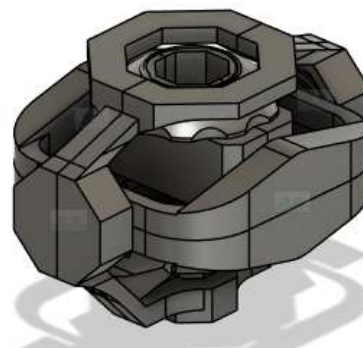
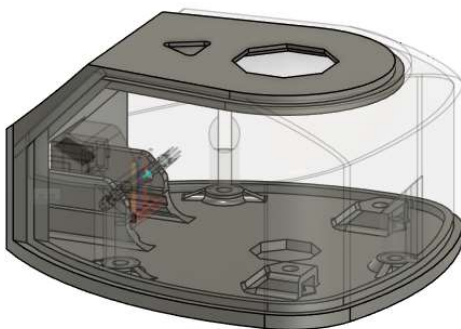
Part	Image	Qty	Description	Link	Price (CAD)
Bearing		4	Bearings for gimbal	Digikey	4.44



Willow Joystick

DESIGN RATIONALE

Magnet		3	Magnets for centering and sensing	Digikey	1.07
M2.5 bolt		5	Bolts to hold magnetic sensor and swappable topper	Digikey	0.20
M2.5 nut		5	Nuts to hold magnetic sensor and swappable topper	Digikey	0.20
M3 nut		2	Bolts to add threads for mounting adaptor	Digikey	0.25
#4 screw		3	Screws to hold enclosure together	Digikey	0.59





Willow Joystick

DESIGN RATIONALE

Electrical Components

Willow Hub

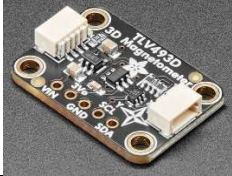


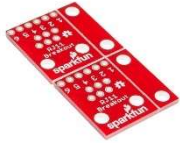
The Willow hub is electrically identical to the LipSync Hub.

https://github.com/makersmakingchange/LipSync/blob/main/Documentation/LipSync_BOM.csv

Willow Joystick

The magnetic sensor is removed from the gimbal, and is instead mounted to the sled. This allows the extensive cable routing to be removed and the wiring simplified. The stemma cable from the magnetic sensor is directly connected to the RJ11 jack that is pinned in place in the enclosure.

Commercial Parts

Part	Image	Qty	Description	Link	Price (CAD)
Magnetic Sensor		1	Sensor to read magnet angle	Digikey	8.64
Stemma Cable		1	Connects the magnet sensor to the jack	Digikey	1.38
RJ11 jack		1	Jack to connect the RJ11 cable	Digikey	1.67
RJ11 breakout		0.5	Jack breakout board	Digikey	3.05



Willow Joystick

DESIGN RATIONALE

Code Structure / Function

The software used is a version of the LipSync code that has been modified to have all pressure and sip/puff functions removed. Other minor changes have also been made, with one of the axis inverted and the deadzone expanded to account for the new sensor location and lower centering force.

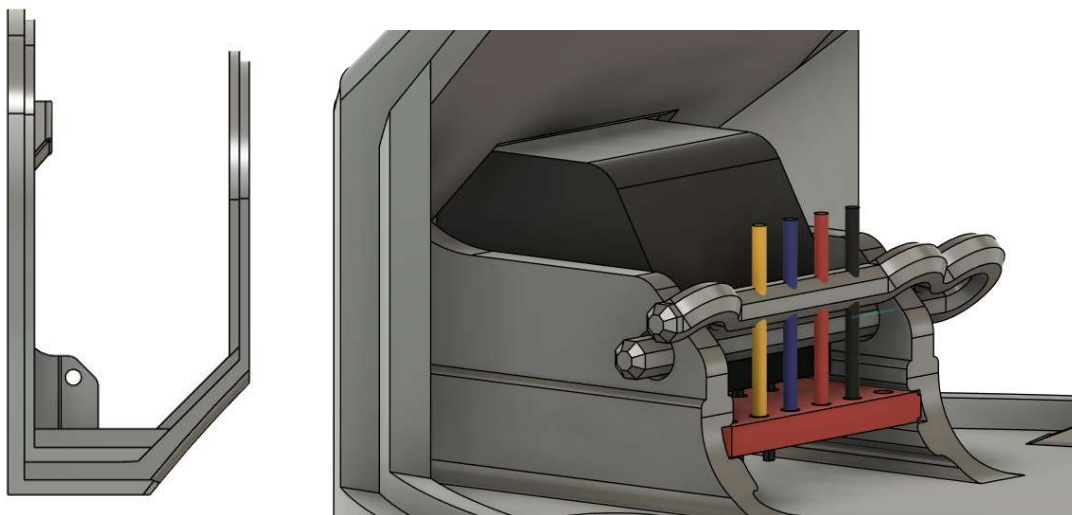
https://github.com/makersmakingchange/LipSync/tree/main/Build_Files/Firmware_Files

RJ11 Jack Retainment

When adding the RJ11 jack to the prototype base, securing the jack to the base proved to be difficult with the print orientation of the base. A snap fit base proved to either be too short to bend properly, or impossible to print due to the overhang, depending on the orientation.

A brainstorming session came up with two alternative ideas, both based around the idea of a sliding track that the jack is inserted in. The first idea was a cotter pin retaining the jack like in the recently redesigned Open Toggle Switch, and the second was a bump in the track that the jack could be forced past but not removed from.

The cotter pin was prototyped first, and found to be so successful that the retaining bump was not developed further due to concerns about being unable to remove the jack for maintenance or repairs of the joystick.



The assembled jack has been tested for strength, and we have been unable to apply enough force to break the jack out of the 3D printed enclosure.



Willow Joystick DESIGN RATIONALE

Testing

MVP Verification

In this test, each of the goals, requirements, evaluation criteria, and constraints were evaluated against the MVP Willow joystick, noting if the device passed or failed.

Test Results

Requirements Testing

Goal	Result	Functional Objective	Result	Non-Functional Objective	Result	Constraint	Result
G01	Pass	F01	Pass	NF01	Pass	C01	Pass
G02	Fail	F02	Pass	NF02	Pass	C02	Pass
G03	Pass	F03	Pass	NF03	Pass	C03	Pass
G04	Pass	F04	Pass	NF04	Fail	C04	Pass
G05	Pass	F05	Pass	NF05	Pass	C05	Pass
		F06	Pass	NF06	Fail	C06	Pass
		F07	Pass	NF07	Pass	C07	Pass
		F08	Pass	NF08	Pass	C08	Pass
		F09	Pass			C09	Pass
		F10	Pass			C10	Pass
		F11	Fail			C11	Pass
		F12	Pass			C12	Pass
		F13	Pass			C13	Pass
		F14	Pass			C14	Pass
		F15	Fail			C15	Pass
		F16	Pass				
		F17	Pass				
		F18	Pass				
		F19	Pass				
		F20	Pass				

MVP Maker Testing

In this test, various makers from within MMC built Willow Joysticks to distribute to clinicians across North America for testing. This section is less of a formal test, and more of an area to note build feedback on the CAD files. Feedback was also gathered on the Maker Guide instructions, but that feedback was directly implemented in the Maker Guide and outside the scope of the Design Rationale.

Test Results

Tester 1

- Magnet in the sled does not want to stay in place without both in place, making it very difficult to assemble





Willow Joystick

DESIGN RATIONALE

Tester 2

- One of the Sled components failed to print
- There is an awkward gap / transition between Joystick Shell and Joystick Base.
- Text on Inner Gimbal is too small to read clearly. Use bigger text or shorter message (e.g., "I1, I2")
- Assembling small machine screws and nuts to mount sensor board is challenging.

Tester 3

- Magnet in the sled does not want to stay in place without both in place, making it very difficult to assemble

Tester 4

- Difficult to read the text on the inner gimbal bodies
- Inner gimbal does not sit flush on the magnets
- Text on outer gimbal is illegible
- Holes for screws on the magnetic sensor are tight
- Sled has some loose space that allows the gimbal to slide in the x direction
- Add a keyed base to the sled so it can't be installed backwards
- Change orientation of the octagon so the corners/slots are in the 8 main directions so the joystick can stick in them
- Make the holes for the machine screws in the base bigger
- Magnet in the sled does not want to stay in place without both in place, making it very difficult to assemble

MVP Characterization Testing

The RJ11 jack was removed from the enclosure, and a hole drilled in the side of the shell. The jack was then fed out the side of the device so that the RJ11 cable would not bend or put extra force on the device if it had to be bend around a section of the jig. The much smaller cables used in the stemma to Dupont cable bend easier and with less force and therefore are less likely to interfere with the force measurements.

Procedure

1. Place the willow orientation jig in the testing jig in the correct orientation for the test that is being performed.
2. Place the willow in the willow orientation jig
3. Gently move the willow along the track until it is just touching the plate of the scale.
4. Extend the calipers until it is just touching the joystick stick.
5. Zero both the scale and the calipers
6. Record the X,Y and Z magnetic sensor readings at 0





Willow Joystick

DESIGN RATIONALE

7. Extend the calipers by roughly 0.5mm. If slightly over or under this, note down the exact distance.
8. Record the force and magnetic sensor readings
9. Repeat step 7 and 8 until the joystick is bottomed out, which can be determined when the force starts increasing much faster than normal and the magnetic sensor readings barely change
10. Repeat this test for each of the 8 directions of the orientation jig. The orientations are labeled below in figure

During initial testing, three issues that arose were the scale turning off during use if the testing took too long, difficulty getting the willow pressed right against the joystick and scale so both zeros are true zeros, and the orientation jig platform lifting up when the centre of gravity of the willow was closer to the scale. This last issue was solved during the testing process by weighing down the side of the orientation jig that was closest to the calipers. Moving the rollers to the edge of the orientation jig also helps to increase the distance from the center of gravity to the point of rotation.

The values of the magnetic sensor were measured using the default Cartesian example from the TLV493D sensor library, modified to provide a reading every 2500 milliseconds, instead of every 500. When observing the results, it was noticed that when the joystick was in a fixed position, it tended to bounce between three results, generally 0.1mT apart. For example, the readings would bounce between 2.76, 2.86, and 2.96. When writing down the measurements for each position, an attempt was made to take the middlemost reading, although occasionally one of the outlier readings may have been taken.

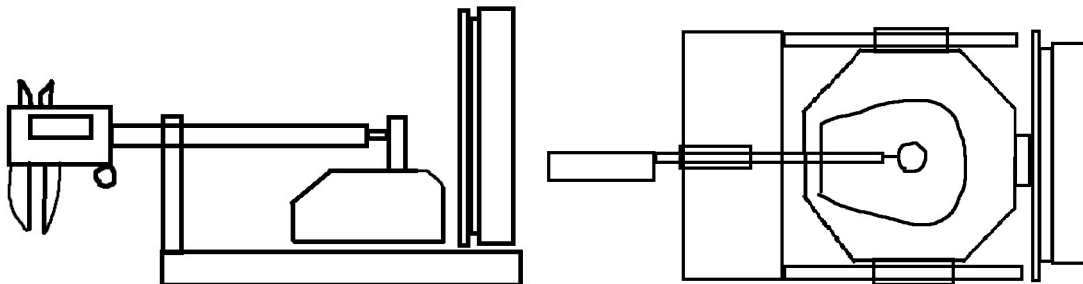


Figure 3: Top View Sketch of Testing Jig(Right)

Figure 4: Side View Sketch of Testing Jig(Left)

Willow Joystick

DESIGN RATIONALE

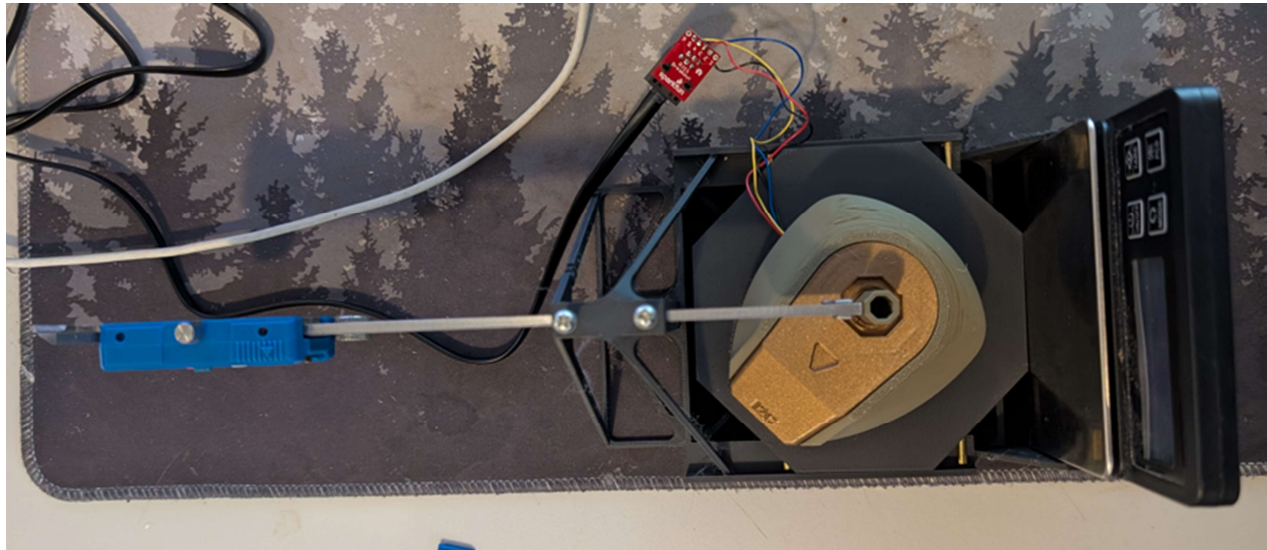


Figure 5:Top View of Testing Jig

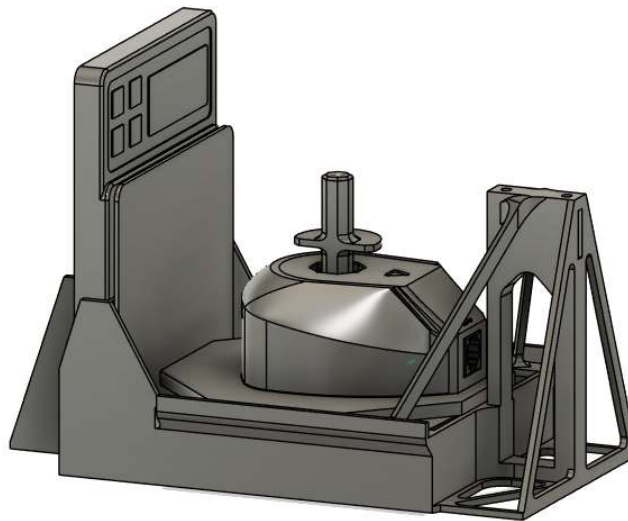


Figure 6:CAD Render of Testing Jig

Willow Joystick

DESIGN RATIONALE

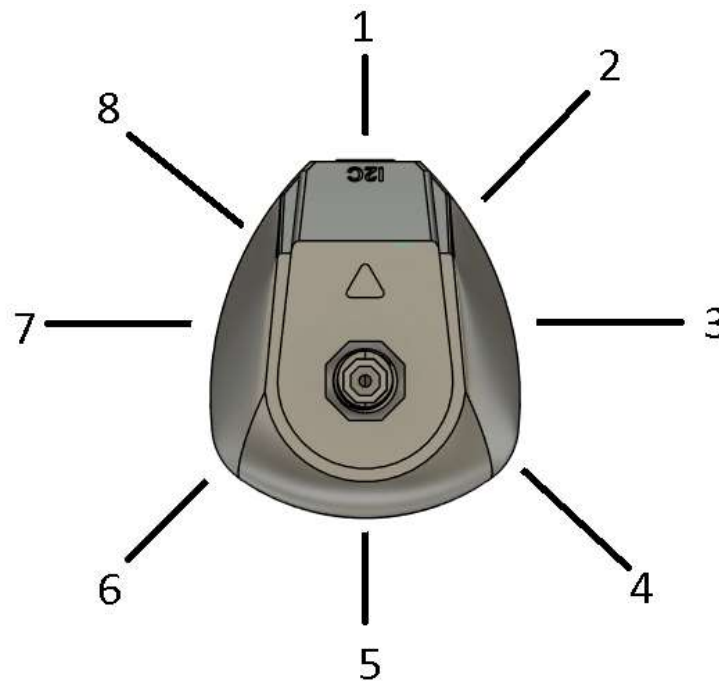


Figure 7:Directions of Testing

For hysteresis testing, the willow was put into debug mode by opening the serial command menu in the Arduino IDE and entering the command “SETTINGS” followed by “DM,1:1”. This makes the willow output the magnetic sensor readings into the serial monitor. For each of the 8 directions, 5 readings at rest will be taken, then the joystick will be displaced and released, with 5 measurements taken when it is back at rest. This process will be repeated 5 times for a total of 6 sets of 5 readings. This procedure will be repeated for all 8 directions.

Test Results

	Mag X Coefficient	Mag X Error	Mag Y Coefficient	Mag Y Error	Sqrt sum of squares
Dir 1	-1.73	0.0083	N/A	N/A	1.73
Dir 2	-1.16	0.0081	1.29	0.021	1.73
Dir 3	N/A	N/A	1.78	0.01	1.78
Dir 4	1.16	0.008	1.23	0.012	1.69
Dir 5	1.65	0.0093	N/A	N/A	1.65
Dir 6	1.16	0.025	-1.32	0.21	1.76
Dir 7	N/A	N/A	-1.82	0.036	1.82
Dir 8	-1.12	0.02	-1.22	0.019	1.66
					1.73

Figure 8:Directional Magnetic Coefficients

Willow Joystick

DESIGN RATIONALE

MVP User Testing

In this test, devices were given to clinicians across the country to test with users and collect feedback. These were MVP devices, that still had some drift while print tolerances and dead zones were being determined.

TEST 1

After the clinicians had had time to test the devices and become familiar with them, they were interviewed about their experience with the device. They were asked question about the following areas

- Were there any issues with setup/use? Did the joystick slide around, was cable management an issue?
- Was the amount of force okay? Was it too much or too little?
- Was the range of motion ok? Could it be better?
- What did you like about the toppers? What did you dislike?
- Would you prefer this device with the hub or as a standalone? If you would prefer it standalone, how much of the hub functions would you be willing to give up?
- What are your thoughts on the device? What were the users thoughts?
- Was it comfortable to use? If not, what made it uncomfortable?

Test Results

Clinician 1

- Some drift was noted
- Asked for either the joystick to be lower profile, or some sort of ramp to be added to raise the hand
- Joystick was slippery on the table
- Prefer an alternative to a bolt to hold the topper in place
- Clinicians liked the lilypad topper and one clinician liked using it without a topper, like a roller ball mouse
- Clinician had no issue with setup, although was already familiar with the LipSync
- Clinician complained about cable crossover/cable management issues, although most of these issues were resolved with the addition of a hub stand instead of resting the hub on the table
- Clinician was interested in updating settings through the computer, they were not aware of the serial API but were interested in a webpage that would let them change the settings
- While using the lilypad (The lowest and therefore highest force topper) the force was noted as in the good to high range
- Range of motion is good
- A standalone version without the hub would be nice, but they also want switch inputs

Clinician 2



Willow Joystick

DESIGN RATIONALE

Clinician 2 did not give any feedback on the Willow

Clinician 3

This device was tested by a clinician, but they will not have a user who will benefit from it until early 2025

- Toppers
 - Convex: Like this topper the most
 - Goalpost: Bolt hole was irritating, and it was a bit too wide for a finger. Maybe make several sizes
 - Concave/Lilypad: Why the cutout? Edge of the cutout digs into the finger. Make it a full circle
 - Stick: Why the ledge?
 - The bolt hole is a concern for crumbs as well as skin build up
- The clinician found it to have a good amount of force
- The clinician liked the range of motion
- The clinician found that it would be useful to have both a hub version and a standalone version.
 - If it was offered as a standalone, make sure to ship it in mouse or gamepad, whatever the user requests
 - While the idea of the hub is nice, some users might not even be able to use the hub so a standalone would be cheaper for them
- The clinician liked that it had a low center of gravity and was not prone to tipping

Clinician 4

- The clinician noted that the device got out of calibration quickly
- The clinician was confused by the hub stand, the quickstart guide did not fully explain the stand
- The clinician had no setup issues, and used the joystick with a mounting arm or a hook and loop patch on a board
- Add more documentation info about the camera mount adaptor
- The clinician liked the range of motion and noted that it was just enough for games to differentiate between walking and running
- The clinician liked the ergonomics and thought adding a ramp to support the hand would be a valuable option
- The clinician like the hub, and had never seen a LipSync before. They especially liked that the button timing allowed users to do 3 different inputs based on just one switch. They mentioned that some clients only can use 2 inputs, so 1 joystick and 1 switch is their limit, and this allows multiple outputs from the single input.
 - Clinician was interested in remapping the outputs to put the most useful outputs on the same switch input.



Willow Joystick

DESIGN RATIONALE

Printer Testing

To this point, all the design work for the Willow has been done on a Bambu Labs P1S printer. This is a relatively high end printer, with highly tuned profiles and automatic bed leveling. Since many of the important features of the gimbal are on the surface that contacts the print bed, and they often have very little contact area with the bed, the decision was made to do a test print with an original Ender 3, with no bed leveling or other advanced features.

When trying to assemble the printed parts, it was found that any degree of elephant's foot from the bed not being appropriately leveled caused the assembly of the gimbal to be extremely difficult, if not almost impossible. However, there were no issues with parts lifting off of the bed due to low contact area.

Because of this difficulty assembling if the bed is not appropriately leveled, it is recommended that only printers with an automatic bed leveling be used when printing a Willow.

Detailed Design

Action items leaving stage 3

- Enclosure refinement
- Wrist ramp. 3D printed or foam
- Replace topper bolt system
- Look into toppers more
- Add feet to enclosure base
- Determine ideal dead zone
- Integrate results of linearity testing into code
- Test print of gimbal on bad printer

Topper System

The test MVP joystick shipped with 4 toppers, a concave topper with a slot cut out for a finger, a convex topper, a goalpost topper, and a stick topper. The clinicians who tested the device had a variety of opinions on the topper, both on the size and shapes of toppers available, and the bolt system used to attach the toppers to the joystick.

The bolt topper system had two main problems that were noted, cleanliness/comfort, and swapability. It was noted that the hole in the topper that the bolt passed through was both uncomfortable to the user as well as a trap for things like crumbs and flakes of skin. The depth of the hole also required a small narrow screwdriver to reach the bolt, which makes it difficult to change toppers during use.



Willow Joystick

DESIGN RATIONALE

In the discussion about this, it was decided to replace the bolt topper system with something more clean, comfortable, and convenient. Ideas such as a gutter lock, snap fit, and threaded insert were discussed.

The requirements for a replacement system are as follows

- The topper must be orientable (a topper such as the goalpost with an orientable feature must be able to be reliably oriented correctly on the joystick)
- The topper attachment system must not require tools to swap the toppers

The criteria for a replacement are as follows

- The topper attachment system should not make the topper less comfortable or more difficult to clean
- The topper should have minimal parts
- The topper should be durable
- The topper should require minimal force to install
- The topper should be easily printable

Gutter Lock

A gutter lock system would have the toppers with two tabs, and two corresponding slots on the gimbal. The topper can be freely inserted down the gimbal, then turned 90 degrees to prevent it from being removed. The tab and channel system would have a detent to hold the topper in the twisted position.

Pros

- The tabs provide the force keeping the topper in place, so the force required to twist it in can be much lower than the force holding the topper in place
- No tools required

Cons

- Existing toppers print in two different orientations, the tabs would need to be designed to print in both orientations.
- Potential for topper to delaminate and leave the tabs stuck in the gimbal

Snap Fit

The snap fit topper would have a set of detents on the topper, and a set of tabs on the gimbal. The

Pros

- Simple insertion and removal
- No tools required

Cons

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- Existing toppers print in two orientations, so the detents would need to be printable in two orientations
- The force to insert the topper and the toppers resistance to being pulled out are the same.

Threaded Topper

A threaded topper would come in one of two forms, a threaded topper or a threaded topper collar. The threaded topper would have a threaded connection on the base of the topper, and a matching interior thread on the gimbal. The topper would then screw into the gimbal.

A topper collar would still have the threads on the gimbal, but the topper itself would not have threads. Instead, it would have a lip or some other feature that a threaded retaining ring would sit over. This threaded collar would thread into the gimbal and provide the clamping force to hold the topper in place.

Pros

- A secure, robust connection
- No tools required
- Holding force is distributed along the length of the entire connection

Cons

- No real control over the orientation of the topper if it is just threaded in
- If using a threaded collar, additional vertical and horizontal clearance is required to allow access to the collar, and it has the potential to interfere with the range of motion and force of the gimbal

After reviewing the pros and cons of each, the gutter lock system provides the most secure connection without requiring tools and with minimal changes required to the gimbal. The twist tabs allow for them to resist more force than it takes to insert them, and it allows them to be oriented accurately instead of stopping when the thread bottoms out.

A modified version of the gimbal and the lilypad topper were created to test this attachment method. The diameter of the inner section of the gimbal had to be reduced by 3mm to create an area for the tabs on the gimbal to pass through and twist into. This means that the diameter of the toppers also had to be reduced to fit into the gimbal. This reduction in diameter also reduces the print bed area which poses a danger when trying to print the toppers with a wider top such as the lilypad topper. The print bed area was low enough that the slicing software automatically added a brim around the topper which also affects the tolerances. The gutter lock system itself worked well, although some refinement of the tolerances is needed. The test did not have the retaining detent, but with some force it inserts in the gimbal and twists a full 90 degrees.

With the print orientation of the toppers and the gimbal, the retaining tabs can be added to the gimbal, and the detents to the topper.



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After printing a gimbal with the gutter lock and tabs, and a topper with the detents, it was found that the systems works well. The slicer added a brim to the topper to allow it to print without being knocked over by the print head, and after the brim was cleared off the topper it fit well in the gutter lock of the gimbal. The tab and detent system had a noticeable click once fully rotated and held its position well.

There are concerns about the longevity of the tab in the gimbal with the possibility that it may get worn down over time. The idea of placing the detent on the gimbal so that the tab that wears down is on the topper which is more easily replaced was examined, but running the detent along the entire length of the slot is more difficult and will wear down faster than passing the detent over ~1mm of plastic on the topper.

After ~20 times inserting and removing the topper, the force required became lower and lower until there was almost no click or noticeable resistance when fully turning the topper. However, after printing a new topper the force required returned to normal, showing that the wear occurs mostly on the much more easily replaceable topper, rather than the inner gimbal itself.

Topper System Decision

After reviewing the gutter lock system and the cons of the other two proposed but unmodeled designs, the decision was made to proceed with the gutter lock system.

Topper Options

The clinician that tested the toppers that came with the Willow had a range of feedback on topper sizes, shapes, and comfort. During the review of the feedback, it was decided to review the topper options to provide more customizable and useful options.

The idea of providing life size images of the toppers in the documentation was discussed, as well as parametric toppers that users customize. The idea of a topper that is compatible with the Xbox Adaptive Thumbstick toppers was also discussed.

Reviewing the topper option for the joysticks currently in the library, there seems to be 6 common types of toppers. The shapes of toppers found in the MMC library include ball, concave, convex, goalpost, stick, and ring. These toppers either come in one size, or in a small, medium, and large size. Earlier in the design process the possibility of reusing toppers from the other joysticks was ruled out, but the choices of style and size of toppers can be used for the design of toppers for the Willow. The larger sizes of toppers would most likely not be feasible due to the weight, but the smaller sizes can likely be duplicated in the Willow.

Topper Selection

When reviewing the gutter lock system on the Willow, the decision was made to proceed with the topper options that were chosen for the MVP prototype, converted to work with the gutter lock system and with the feedback from the users incorporated, such as making the goalpost topper wider and removing the groove from the concave lily pad topper.



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The decision was also made to create a topper that is based on one of the [Xbox adaptive thumb sticks](#), designed to have a large amount of surface area for heat mouldable plastic pellets to adhere to allow clinicians and users to create their own custom topper without needing to know 3D modelling and printing.

Additionally, the 3D design file for a blank topper with just the gutter lock and stem was made available so that makers can create their own toppers that are fully compatible with the Willow.

Hub

One of the goals of the testing feedback was to determine the output architecture of the Willow. While a number of options were considered, the two primary categories that they fell into was a hub, or a standalone joystick.

The version of the Willow that was shipped to testers used a reprogrammed LipSync Hub to provide switch inputs, visual and audio feedback, and contained the microcontroller for the device. The testers were asked if they liked the hub, or if they would prefer a standalone device, and what they would give up to get to a standalone device.

Every clinician that tested the device liked the hub and the options that it provided, but said that they would also be interested in a standalone version. The testers that specialized in computer access especially liked the built in switch access, as well as having multiple computer outputs from a single switch input with different press timings. The testers who focused on accessible gaming did not mention switch inputs, likely due to using intermediary systems such as the Xbox Accessible Controller (XAC) that already have switch inputs. A point that was raised by one tester is that some users may not be able to use the hub to change settings so a standalone version would prevent them from having to spend extra money on a hub that they cannot use.

The LipSync Hub used with the Willow was programmed with a modified version of the LipSync code. Since the Willow works on the same principle as the LipSync, the pressure sensing parts of the LipSync code could be removed and the axes directions inverted to create a working version of the Willow that maintains the input, output, and feedback options of the LipSync.

The results of this testing show two different use cases for the Willow, the complete solution and the solution component. The complete solution is used in computer access situations, where the Willow Joystick, Willow Hub, and up to three switches are used to control a device such as a computer or mobile phone. The solution component is used in accessible gaming solutions where the Willow Hub and Willow Joystick are connected to another device that has other accessible technology connected to it, such as a XAC or a computer with a rocket switch interface.

The complete solution Willow requires the switch inputs of the Willow Hub and is improved by the user feedback options that the hub provides. The solution component Willow does not require the switch inputs of the Hub, but is not made worse by having them available. The main downside to using the Willow Hub in a solution component use case is the additional cost of building the Hub, which costs

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DESIGN RATIONALE

~\$110 CAD in addition to the ~\$50 CAD joystick. A standalone joystick is estimated to cost ~\$70-80, depending on what inputs and outputs the joystick has.

Considering the different use cases for the willow and the two possible paths for a standalone or hub Willow, the recommendation is to carry forward with the hub version of the Willow. It already exists, with a working code base that needs minimal changes to get it release worth. It provides a large number of feedback and input options while keeping the joystick simple enough to be potentially compatible with any of the i2c compatible hubs in the MMC library.

However, there is a case for a standalone version of the Willow for users looking for a low cost option, users who have no need for the number of inputs/outputs the Willow provides, or users who are using the Willow as part of a larger accessibility solution. The physical gimbal system itself would not need to be changed, but a new enclosure would need to be designed to allow for the microcontroller and possible a small number of input switches or output lights, as well as a modification of the existing codebase or creation of a new codebase.

Joystick Height

One of the most common complaints raised about the Willow was the height of the joystick. Even after redesigning it from the LipSync gimbal to reduce the height as much as possible, the clinicians still felt that it was too tall. This feedback about height also came with a request for a ramp of some sort to raise the height of the user's hand relative to the joystick.

Enclosure modification One option for raising the users hand relative to the Willow is a modified enclosure that provides a more gentle slope for the hand to rest on. This slope can either be build into the enclosure, or an optional enclosure add on as seen on the Aspen Joystick. However, the customizability is limited by the need to fit the gimbal or the existing enclosure, and it also is limited to only be used with the Willow joystick.

Foam ramps to raise the user's hand relative to the joystick can be purchased commercially, or DIYed by a clinician out of foam. A parametric 3D printable ramp will also be designed and added to the project files for a easy to customize low effort way to elevate the user's wrist.

Anti-Slip Feet

One of the most consistent pieces of test feedback received was that the joystick tended to slip and slide on the table when used. The addition of non slip feet was already planned, and this feedback increased the priority of this change.

The primary challenge with adding non slip feet is finding an appropriate foot to use. They are commonly available at dollar stores, but the varying diameters and thicknesses of the feet make it difficult to add design features to the base to accommodate them. After searching on Digikey, a suitable option was found. The foot was both small and thin, as well as available to be purchased individually instead of in bulk. A sample set was ordered to test the actual non slip ability of the feet, and they were found to be suitably resistant to sliding.



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DESIGN RATIONALE

The design of the base was modified to allow the addition of the feet. The length of the enclosure had to be increased to allow clearance for the feet when the camera mount adaptor is attached.

The feet were initially placed to cover the screw holes on the base of the enclosure, but it was found that when placed over the screw holes, the spacing required for the camera mount adaptor caused the joystick to be prone to rocking when a strong force is applied to the 'southeast' or 'southwest' direction of the joystick.

To limit the tipping, a variety of solutions were considered. These solutions were a rim around the base in addition to the feet, widening the base so that there is room to have the feet beside the camera adaptor, replacing the feet with a piece of Dycem, rotating the camera mount adaptor to make space for the feet, and a second adaptor that bolts onto the camera adaptor nuts to add feet that can be removed and replaced with the camera mount adaptor.

Adding a rim around the base of the willow would help prevent rocking, but would need to be precisely the right height to allow the feet to contact the surface to limit slipping, while also not allowing the device to tip. This rim height would be dependent on the feet used, so if the maker used anything other than the feet linked in the BoM, the rim would not work.

Widening the base to move feet to outside of camera adaptor was tested, and it was found that it greatly increased the size of the enclosure, and created dead space inside the enclosure. This increased size restricts positioning options and may make the device more cumbersome for the user.

Dycem is a frequently used option that provides non slip with minimal added height, but has the downside of requiring the purchase of an entire roll. This would be a good option for therapists or other AT professionals who may have it on hand already, but could be cost prohibitive for a maker who does not already have a roll.

The idea of rotating the camera mount 90 degrees to provide room for the feet was examined but discarded after it was discovered that it would interfere with the RJ11 jack.

Finally, the idea of creating a separate foot, similar to the one used in the testing jig was proposed. The foot would have slots for the non slip pads, and bolt to the same embedded nuts that the camera adaptor does. This would allow for the foot to be removed when the camera adaptor is needed, and also allows for Dycem to be used instead of the foot if the user has it on hand.

After printing the non slip foot, it was found that it raised the height of the joystick by 4mm, and did not have any tipping issues under normal or forceful use.



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DESIGN RATIONALE

Design Validation Plan

Executive Summary

Test Plan

Due to the thoroughness of the testing done in Stage 3, the testing in this section will be focused on the changes made in Stage 4 as a result of the feedback gathered.

Evaluate Final Product vs Initial Requirements, Goals, and Constraints

- Evaluate each of the goals, functional requirements, nonfunctional requirements, and constraints against the current design
- If any fails, explain why

Evaluation of Gutter Lock Toppers

- Get 3 makers to do a test print and get feedback
- Determine the approximate force required to lock the topper in place with a fresh print
- Get clinician feedback on toppers

Evaluation of Non-Slip Base

- Determine how much force is required to cause the device to slip on a smooth desk surface
- Determine how much force is required to tip the device when applied to each topper
 - Test for each of the four 'lines' between the nonslip feet

Evaluation of Wrist Ramp

- Get 3 makers to do a test print and get feedback
- Change the parametric settings ~25% to see if any design features are prone to breaking
- Get a test print to a clinician for feedback

Test Results

Evaluate Final Product vs Initial Requirements, Goals, and Constraints

Evaluation of Gutter Lock Toppers

Evaluation of Non-Slip Base

Evaluation of Wrist Ramp

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DESIGN RATIONALE

Finalized Willow

The final version of the Willow that is being published as V1.0 consists of two separate components. The first component is the Willow Joystick, and the second component is the Willow Hub.

The Willow hub is almost identical to the LipSync hub, with the only difference being the label on the enclosure and the firmware that it is running. The firmware is a modified version of the LipSync firmware that has all the sip and puff functionality removed.

The Willow Joystick uses the same magnetic gimbal concept as the LipSync, but with the sip and puff sensors removed, and the gimbal redesigned to make it lower profile. The mouthpiece of the LipSync has been replaced by a set of gutter lock toppers.





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Goal	Result	Functional Objective	Result	Non-Functional Objective	Result	Constraint	Result
G01	Pass	F01	Pass	NF01	Pass	C01	Pass
G02	Fail	F02	Pass	NF02	Pass	C02	Pass
G03	Pass	F03	Pass	NF03	Pass	C03	Pass
G04	Pass	F04	Pass	NF04	Fail	C04	Pass
G05	Pass	F05	Pass	NF05	Pass	C05	Pass
		F06	Pass	NF06	Fail	C06	Pass
		F07	Pass	NF07	Pass	C07	Pass
		F08	Pass	NF08	Pass	C08	Pass
		F09	Pass			C09	Pass
		F10	Pass			C10	Pass
		F11	Fail			C11	Pass
		F12	Pass			C12	Pass
		F13	Pass			C13	Pass
		F14	Pass			C14	Pass
		F15	Pass			C15	Pass
		F16	Pass				
		F17	Pass				
		F18	Pass				
		F19	Pass				
		F20	Pass				

Opportunities for Improvement

Physical Component / Enclosure

There are several opportunities for improvement with the 3D printed parts of the Willow.

- A custom camera mount adapter could be created that blends better with the enclosure
- The enclosure could be modified with a built-in optional weight to remove the need for a nonslip foot.
- The M3 nut captures on the base could be redesigned to be more in line with the nut captures used on the existing OpenAT joysticks
- Modify the toppers to have wrench flats and add a 3D printable wrench to the build files.
- The indents for the feet on the nonslip pad could be made larger to accommodate a larger variety of non slip feet.

Code Structure / Function

The primary opportunity for code improvement is to merge the code base of the willow and the LipSync so that changes to one do not need to be duplicated to the other and to allow the hubs to be interchangeable without needing to reprogram them.