Mechaduino

(hardware versions 0.1, 0.2)

an open source industrial servo
from Tropical Labs

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Introduction

Mechaduino is an Arduino for mechatronics! Mechaduino is a self-contained motion control platform which allows you to develop your own custom servo mechanisms. It can be also be used as a drop-in servo motor for 3D printers and CNC machines. No more missed steps!

Updates

In this version of the Mechaduino Manual, we've added documentation for the new Mechaduino 0.2 hardware. This new hardware is backwards compatible with the Mechaduino 0.1 and features the following improvements:

- Four 5V level-shifted digital I/O (D0, D1, D2, & D3)
- Better thermal design for A4954 driver
- Higher voltage capacitors allow for a max V+ of 35V
- Small vias provided to break out encoder A/B/I interface and rsense voltages (for experimental use)
- No more traces under mounting screws*
- No traces under AS5047 encoder
- Simplified power circuit

Additionally, we've made a couple minor adjustments to the firmware, which supports both the original Mechaduino 0.1 and the updated Mechaduino 0.2:

- Fixed bug in menu
- Changed 'oneStep()' and calibration routine to use one phase at a time. This seems to reduce noise in the calibration lookup table.

*Bottom solder mask under OSHW logo can be scraped away to provide single ground point to motor.

Overview of Specifications

Microcontroller: SAMD21G18A

ARM Cortex-M0+ CPU running at 48MHz
Arduino Zero compatible
Operating Voltage: 3.3V
NOTE: only pins D0 and D1 have level converters for use with 5V logic. All others are 3.3V

Encoder: AS5047D

Resolution:	14bit
Accuracy:	about ±0.1° worst case after calibration routine*
Interface:	SPI

Motor Driver: A4954

Dual Full-Bridge DMOS PWM Motor Driver
Peak output currents: ±2 A

Motor included with Mechaduino Servo: 17HS16-2004S1

Motor Type:	Bipolar Stepper
Step angle:	1.8°
Holding Torque:	45Ncm (63.7oz.in)
Rated Current/phase:	2A
Phases:	2
Positional accuracy:	±5%
Phase Resistance:	1.1ohms
Inductance:	2.6mH±20%(1KHz)
Rotor Inertia	54gcm^2
Frame Size:	NEMA 17 (42mm X42mm)

*This is limited by the positional accuracy of the stepper motor that you use. This encoder has an integral nonlinearity of up to ±0.8°. Our calibration routine uses the stepper motor’s full step positions as references to calibrate out most of this error. Most stepper motors claim a full step accuracy of ±5% or better.

Magnet: Diametrically Magnetized NdFeBr

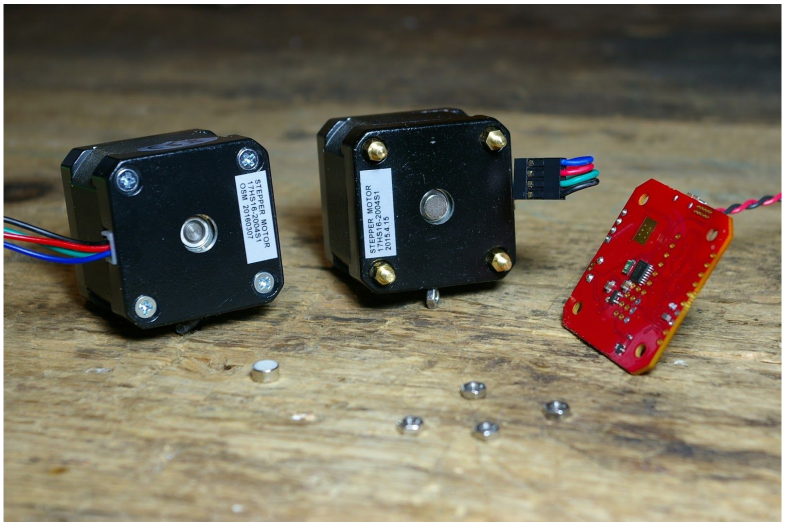
Mount about 1mm-2mm from encoder chip. Use epoxy/superglue to secure to shaft. Calibration routine corrects for minor misalignment.

Mounting Hardware:

We use m3 threaded rods epoxied into 4mm M3 standoffs. Be careful not to remove all motor screws at once while installing: Opening a stepper motor can weaken its magnetization.

Getting Started

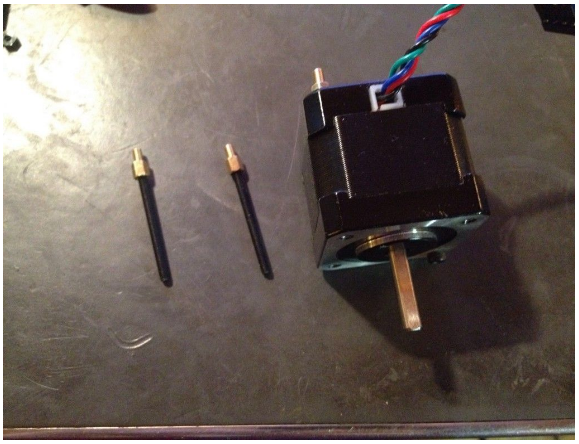
Assembly:



You will need to mount the magnet to the back of the motor shaft. *Note: the magnet must be diametrically magnetized, as opposed to axially magnetized.* The magnet may naturally stick to the shaft, but we recommend a dab of epoxy or super glue to hold it in place. The magnet should be fairly centered, but the calibration routine will correct for minor misalignment.

The Mechaduino PCB must be mounted so that the magnet is directly under the encoder chip. (Close but not touching. About 1-2mm. See the AS5047 datasheet for details.) We replaced the standard motor hardware with M3 threaded rods and short standoffs to mount on our Mechaduinos, but there are other ways this could be done.

When wiring your motor up to the Mechaduino board, please make sure that one phase is connected to outputs 1&2, and the other phase is connected to outputs 3&4.



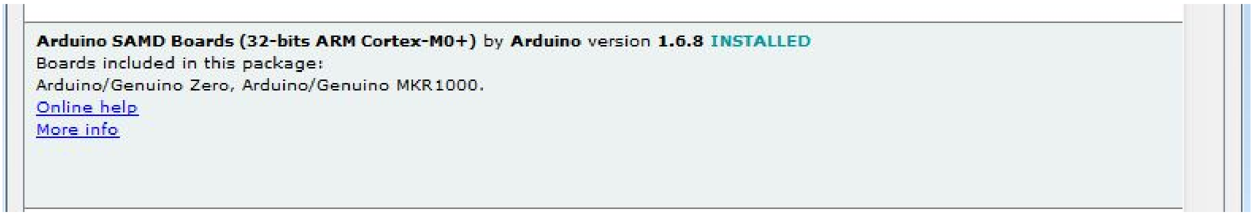
Firmware:

Next, you need to install the firmware:

The Mechaduino firmware can be compiled/edited/uploaded using the popular Arduino IDE:

https://www.arduino.cc/en/Main/Software

Once you have the Arduino IDE installed, you will need to add Arduino Zero support. Open the Arduino IDE, navigate to Tools>Board:...>Board Manager and install the latest "Arduino SAMD (32-bits ARM Cortex-M0+)" .



Arduino SAMD Boards (32-bits ARM Cortex-M0+) by **Arduino** version **1.6.8** INSTALLED
Boards included in this package:
Arduino/Genuino Zero, Arduino/Genuino MKR1000.
Online help
More info

At this point you you can connect your Mechaduino via USB. It will appear as an Arduino Zero. (If it does not appear, please make sure any drivers have finished installing, then try hitting the reset button or disconnecting/reconnecting the hardware...see note below)

Download the latest Mechaduino_01 firmware (the 'master' branch on GitHub), open it in the Arduino IDE, compile it, and upload to your Mechaduino. Previous versions of the firmware are available here.

1.8 vs 0.9 degree steppers:
By default the firmware assumes a 1.8 degree (200 steps per rev) stepper. If you are using a 0.9 degree (400 steps per rev) or other size stepper, you will need to adjust the parameter "spr" (steps per rev) in parameters.cpp.

```
const int spr = 200;  // 200 steps per revolution -- for 400 step/rev, you only need to edit this value
```

**NOTE:*
Apparently the arduino zero drivers do not always automatically install. Please take a look at these instructions:
https://www.arduino.cc/en/Guide/ArduinoZero
I have had issues where it will show up in the device manager, but not as a COM port (as an unidentified device). If this is the case, the bootloader is present, but the drivers have not installed properly.

Calibration Routine:

Once you have the firmware installed, you will need to run the encoder calibration routine. With the Mechaduino connected to your computer, open a serial monitor (115200 baud) in the Arduino IDE. You will need to provide V+ to the Mechaduino to power the motor drivers (needed to calibrate). Type "s" and press enter a couple times to verify that everything is working. The Mechaduino should step like a stepper. It is currently in open loop mode. press "d" and the stepping direction will change.

Now, make sure nothing will touch the Mechaduino shaft during the calibration routine. Type "c" to start the calibration routine. The Mechaduino will now step through all full steps to calibrate the encoder. When the routine is done, a very long lookup table (16,384 entries) will be printed to the serial terminal. These are the calibrated angles at each encoder count. You will need to copy these into the Parameters.cpp file here:

```
//This is the encoder lookup table (created by calibration routine):

const float lookup[] = {
//Put lookup table here!
};
```

You can easily select the whole lookup table from the serial monitor by clicking on the next line and dragging the cursor up.
Save, compile, and re-upload the firmware to your Mechaduino. Your Mechaduino is now calibrated.

Basic Commands:

As long as you have "serialCheck();" in your main loop, you can use the following built in commands to control the Mechaduino from a serial monitor:

Implemented serial commands are:

```
s  -  step   (steps one full step in open loop mode)
d  -  dir    (changes step direction in open loop mode)
p  -  print angle [step count] , [assumed angle] , [encoder reading]

c  -  calibration routine
e  -  check encoder diagnostics
q  -  parameter query     (prints current PID values and cal table)

x  -  position mode            (set mode for closed loop operation)
v  -  velocity mode
t  -  torque mode

y  -  enable control loop      (enter closed loop mode)
n  -  disable control loop     (go back to open loop mode)
r  -  enter new setpoint       (new setpoint for control loop)

j  -  step response
k  -  edit controller gains*
g  -  generate sine commutation table
m  -  print main menu
```

See serialCheck() in Utils for more details

*Note, these edits are stored in volatile memory and will be reset if power is cycled

Tune Control Loop:

At this point you may need to tune the controller gains. By default, the position and velocity loops have PID controllers with parameters that can be edited in Parameters.cpp:

```
//----Current Parameters-----

volatile float Fs = 6500.0;   //Sample frequency in Hz

volatile float pKp = 10.0;      //position mode PID values.
volatile float pKi = 0.15;
volatile float pKd = 20.0;


volatile float vKp = 0.05;       //velocity mode PID values.
volatile float vKi = 0.033;
volatile float vKd = 3.0;
```

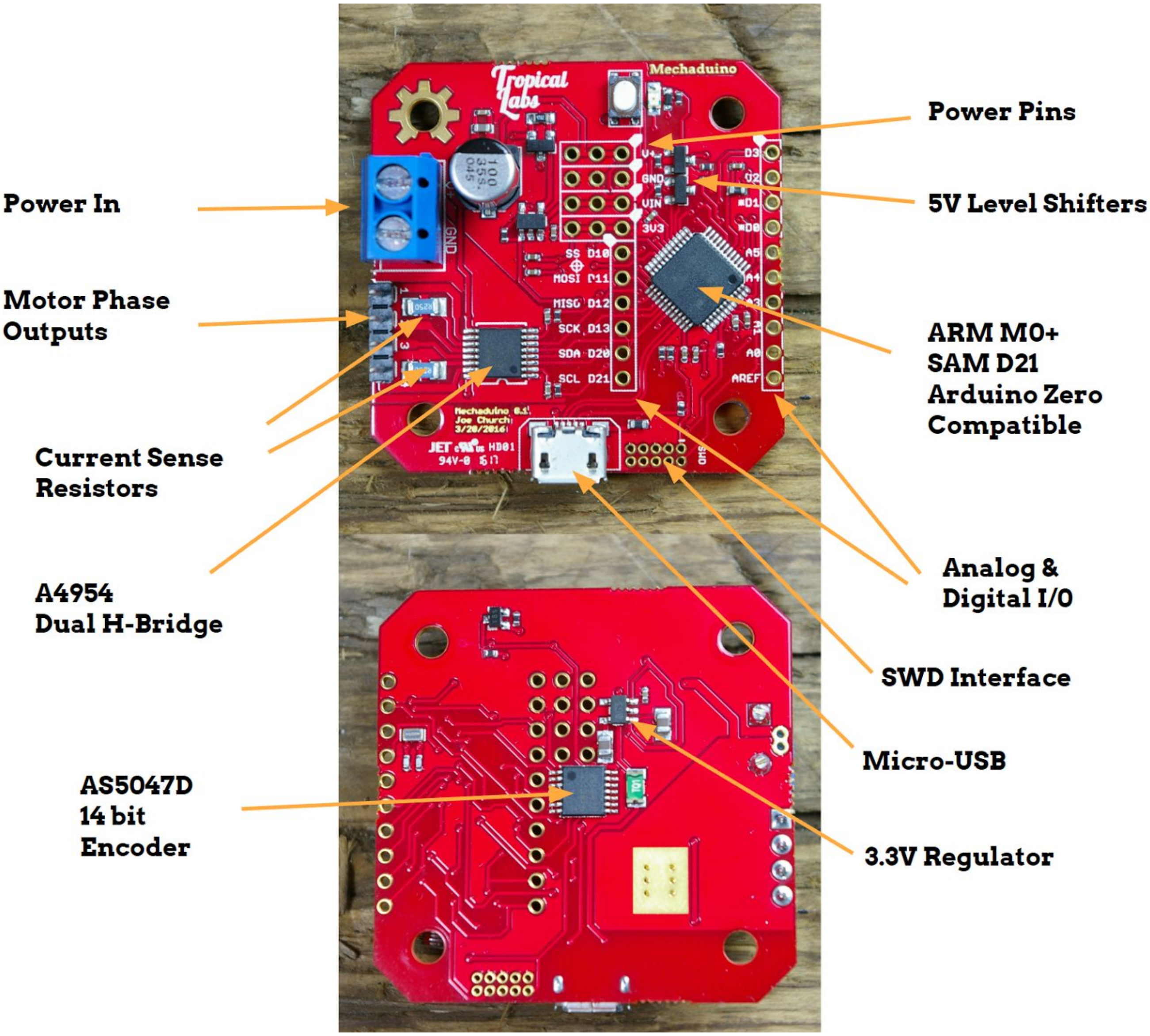
To tune the control loop from the serial monitor:

- Connect your Mechaduino to your computer and open up a serial monitor
- Use the commands ‘x’ followed by ‘y’ to enter closed loop position mode
- Use the command ‘k’ to bring up the tuning menu
- Adjust the parameters until you get a good response
- To make these changes permanent, you will need to copy these values into the Parameters.cpp file and re-upload.
- You can compare tunings by using the step response command ‘j’. (You must exit the tuning menu first.)

PID values will vary a lot depending on the motor you use and the load you have connected to your motor. There are lots of resources online that discuss PID tuning, but here are some simple pointers:
-Start with a low proportional gain and no integral or derivative action. If the motor seems to buzz or behave erratically, then your Kp is probably too high. Try setting Kp low enough that the motor behaves like a fairly compliant spring about the setpoint.
-Slowly increase Kp to improve the stiffness of the control. Adding integral action can remove steady state errors. Derivative action can also be added in to improve performance.

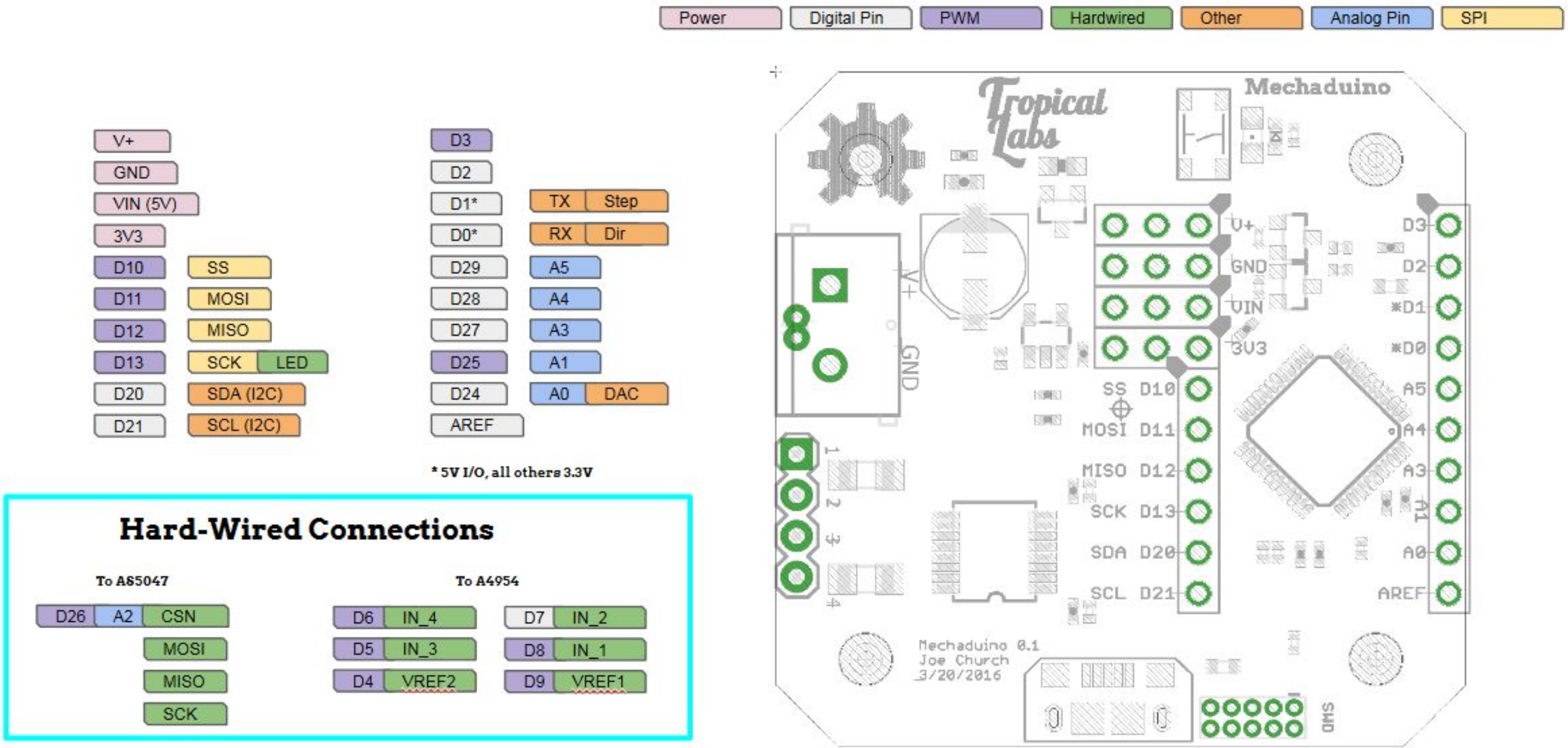
Hardware:

Board Layout



Version 0.1 shown, version 0.2 is very similar.

Pin Diagram

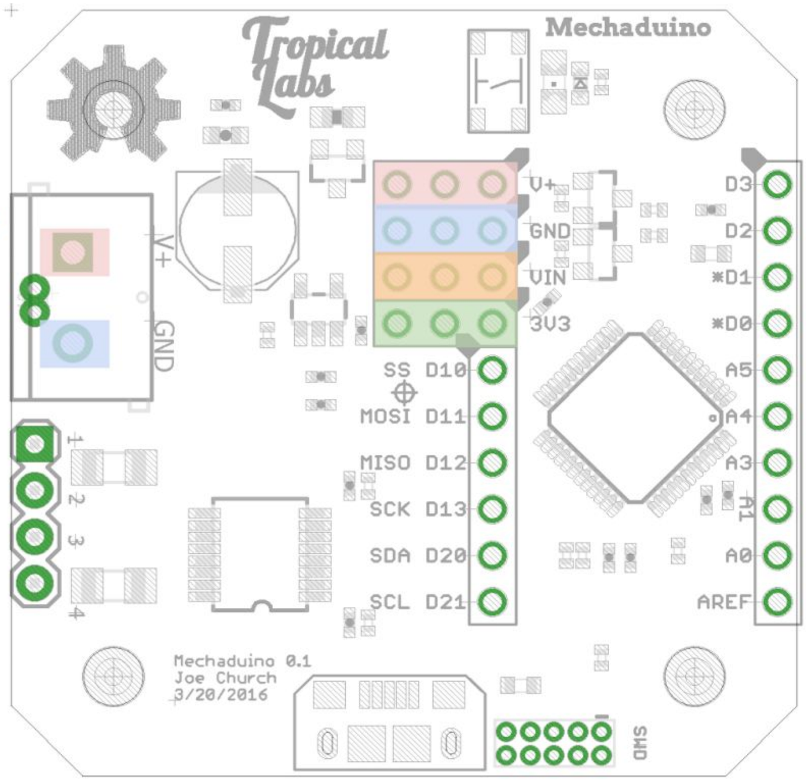


For more info, see schematic!

Version 0.1 shown, version 0.2 has four 5V I/O : D0,D1,D2,& D3.

Power Connections

V+	**Motor Power:** **Mechaduino 0.1:** V+ = 8V - 25V **Mechaduino 0.2:** V+ = 8V - 35V
VIN (5V)	**5V Logic Supply** (See below)
3V3	**3.3V Logic Supply, Regulated from VIN (5V)**
GND	**Ground (Logic and motor ground are tied at single point)**



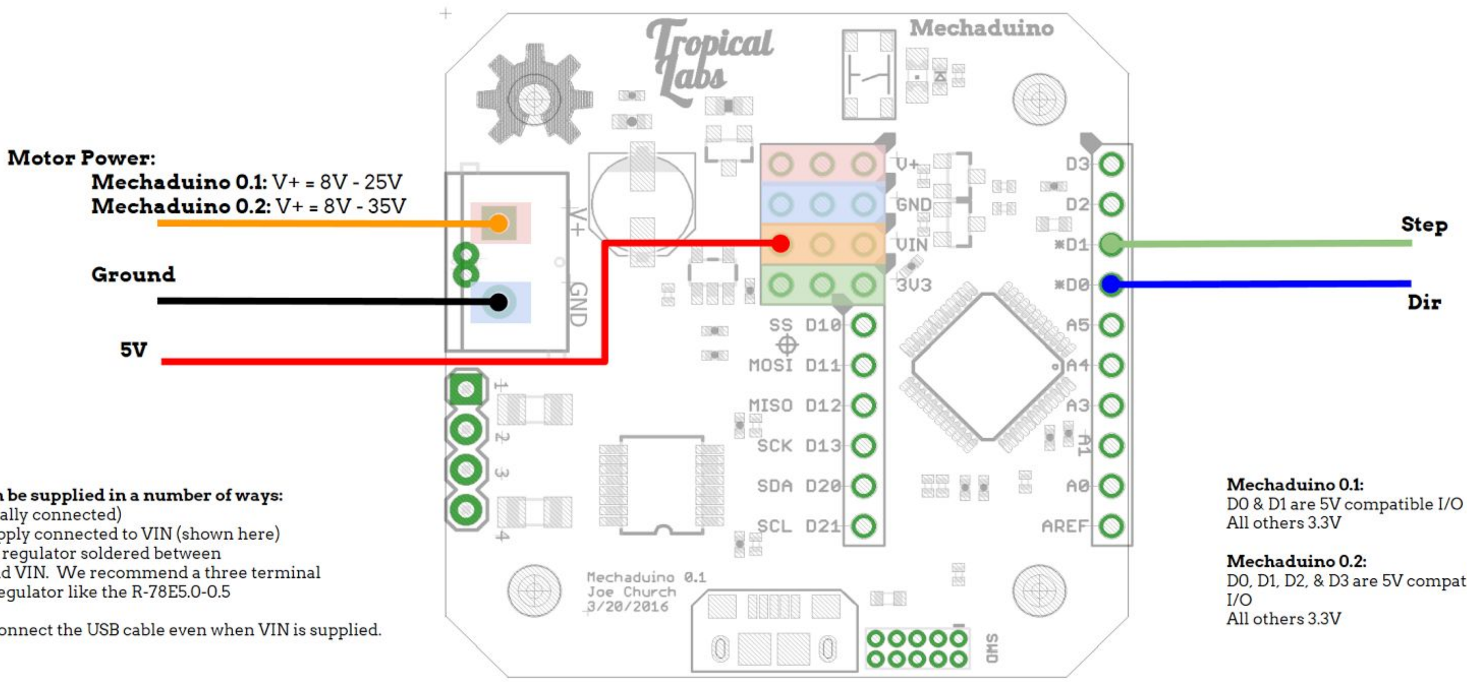
VIN can be supplied in a number of ways:
-USB (Internally connected)
-External supply connected to VIN
-External 5V regulator soldered between V+,GND, and VIN. We recommend a three terminal switching regulator like the R-78E5.0-0.5

It is safe to connect the USB cable even when VIN is supplied externally. Mechaduino 0.1 only: If the Arm M0+ is configured as a USB host, VIN will automatically source to an external USB device.

For more info, see schematic!

Step/Dir Wiring Diagram

For more info, see schematic!



VIN (5V) can be supplied in a number of ways:

-USB (Internally connected)
-External supply connected to VIN (shown here)
-External 5V regulator soldered between V+,GND, and VIN. We recommend a three terminal switching regulator like the R-78E5.0-0.5

It is safe to connect the USB cable even when VIN is supplied.

Mechaduino 0.1:
D0 & D1 are 5V compatible I/O
All others 3.3V

Mechaduino 0.2:
D0, D1, D2, & D3 are 5V compatible I/O
All others 3.3V

Firmware v0.1.4

Overview

The Mechaduino Firmware can be edited, compiled and uploaded from the popular Arduino IDE. It is written in Arduino language (similar to C/C++). You can script the Mechaduino's behavior in the main loop of the file *Mechaduino_01.ino*. The stock Mechaduino firmware is configured to listen for serial commands using `serialCheck()`. A step/dir interrupt can be enabled to increment/decrement the setpoint variable.

Files

Mechaduino_01.ino

This is the main file that contains `setup()`, which runs once on startup and `loop()` which runs thereafter.

Controller.cpp

Contains the TC5_Handler() which executes at 6.5kHz* when enabled and contains the closed loop control algorithms. For more info on configuring TC5, please see this.

Parameters.cpp

Contains configurable parameters including PID gains, calibration table, and other constants.

State.cpp

Contains controller state variables.

Utils.cpp

Contains utility function definitions.

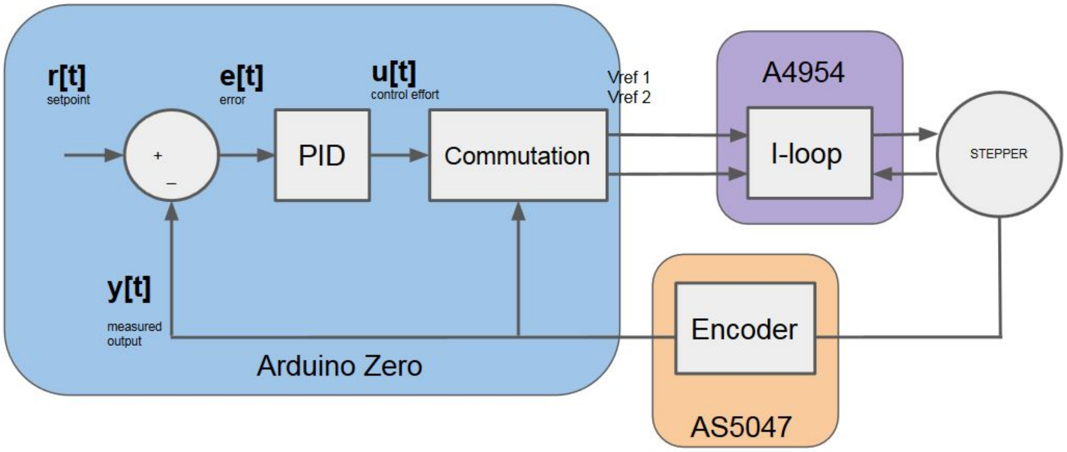
AnalogFastWrite.c

The latest arduino zero board files (1.6.7 and up) have a much lower PWM frequency than previous versions (732.4Hz , down from 187.5kHz). This causes audible hissing when used with the Mechaduino. We added the analogFastWrite command to provide 187.5kHz PWM to eliminate this issue.

Additionally, the header files (.h) contain function declarations and macro definitions for the above files. *Utils.h* is a good reference since it gives a list of all the implemented utility functions.

*Set by `Fs` in Parameters.cpp which changes `TC5->COUNT16.CC[0].reg = (int)( round(48000000 / Fs));` in `setupTCInterrupts()` in *Utils.cpp.*

Block Diagram



In code,
r[t] is written as `r`,
r[t-1] is written as `r_1`

Variables

Important global variables include controller state variables and configuration parameters. While the use of global variables is sometimes frowned upon, we wanted these values to be accessible and modifiable to make it easier to develop custom applications (see the example section of this document). Similarly, we chose to use floating point math for the controller instead of fixed point math. While fixed point math would be faster, we've found that our floating point algorithms are generally fast enough, and are much more readable. As a result, many of these variables are floats. Here is an overview:

Name	Description	Type	range	unit	Definition Location
r	Control loop setpoint	float	N/A	Degrees in position mode….	State.cpp
y	Corrected encoder reading	float	0.0 to 360.0	degrees	State.cpp
yw	Wrapped angle (keeps track of revolutions)	float	N/A	degrees	State.cpp
e	Error (r-yw)	float	N/A	degrees	State.cpp
u	Control effort	float	-uMAX to uMAX	Bits (8.6mA/bit)*	State.cpp

(3.3V/255bits)(1A/10*rsense)= 8.6mA

Control Algorithms:

Position Mode:

The default **position mode** controller is a PID controller of the following form (represented as discrete transfer functions using the z-transform):

$$u(z) = Pterm(z) + Iterm(z) + Dterm(z)$$

$$e = r - yw$$

$$\frac{Pterm}{e}(z) = pKp$$

$$\frac{Iterm}{e}(z) = \frac{pKi\, z}{z-1}$$

$$\frac{Dterm}{y_w}(z) =- pKd * (1-a)\frac{(z-1)}{(z-a)}$$

In code, this is implemented with the following difference equations:

```
        e = (r - yw);

        ITerm += (pKi * e);                             //Integral wind up limit
        if (ITerm > 150.0) ITerm = 150.0;
        else if (ITerm < -150.0) ITerm = -150.0;

        DTerm = pLPFa*DTerm -  pLPFb*pKd*(yw-yw_1);

        u = (pKp * e) + ITerm + DTerm;
```

A couple notes:

-Dterm is calculated from angle measurement, yw, rather than from error. This is a common practice that prevents jumps from step reference commands, but provides the same damping. (This is why there is a negative sign: e = r - y)

-Dterm has a first order low pass filter. The breakpoint of the filter is set by adjusting pLPF (in hertz) and is calculated as follows:

$$a = e^{(sT_s)} = e^{(-pLPF*2pi*T_s)}$$

(in code, a is pLPFa)

Velocity Mode:

The default **velocity mode** controller is a PID controller of the following form (represented as discrete transfer functions using the z-transform):

$$u(z) \ = \ Pterm(z) \ + \ Iterm(z) \ + Dterm(z)$$

$$\frac{v}{yw} = -\,(1-a) * \ Fs \ * \ 0.16666667 * \frac{(z-1)}{(z-a)}$$

$$e \ = \ (r \ - \ v);$$

$$\frac{Pterm}{e}(z) \ = \ pKp$$

$$\frac{Iterm}{e}(z) \ = \ \frac{pKi\,z}{z-1}$$

$$\frac{Dterm}{e}(z) = pKd * \frac{(z-1)}{(z)}$$

In code, this is implemented with the following difference equations:

```
         v = -(vLPFa*v +  vLPFb*(yw-yw_1));     //filtered velocity

          e = (r + v);   //error in degrees per rpm (sample frequency in Hz*(60 seconds/min)/(360 degrees/rev))

          ITerm += (vKi * e);                  //Integral wind up limit
          if (ITerm > 200) ITerm = 200;
          else if (ITerm < -200) ITerm = -200;

          u = ((vKp * e) + ITerm - (vKd * (e-e_1)));
```

A couple notes:

v, the filtered, measured velocity, has a first order low pass filter. The breakpoint of the filter is set by adjusting pLPF (in hertz) and is calculated as follows:

$$a \ = \ e^{(sT_s)} = e^{(-pLPF*2pi*T_s)}$$

(in code, a is vLPFa)

Torque Mode:

In **torque mode**, the setpoint `r` directly sets the control effort `u`, which in turn sets the current level. The a4954 driver chip has an internal current loop that forces the motor phase current to the commanded level. The torque exerted by the Mechaduino is equal to the motor torque constant times the phase current.

Functions

```
void setupPins();                 // initializes pins

void setupSPI();                  // initializes SPI

void configureStepDir();          // configure step/dir interface

void configureEnablePin();        // configure enable pin

void stepInterrupt();             // step interrupt handler

void dirInterrupt();              // dir interrupt handler

void enableInterrupt();           // enable pin interrupt handler

void output(float theta, int effort);   // calculates phase currents (commutation) and outputs to Vref pins

void calibrate();               // calibration routine

void serialCheck();               // checks serial port for commands.  Must include this in loop() for serial interface to work

void parameterQuery();            // prints current parameters

void oneStep(void);               // take one step

int readEncoder();                // read raw encoder position

void readEncoderDiagnostics();    // check encoder diagnostics registers

void print_angle();               // for debugging purposes in open loop mode:  prints [step number] , [encoder reading]

void receiveEvent(int howMany);   // for i2c interface...

int mod(int xMod, int mMod);      // modulo, handles negative values properly

void setupTCInterrupts();         // configures control loop interrupt

void enableTCInterrupts();        // enables control loop interrupt.  Use this to enable "closed-loop" modes

void disableTCInterrupts();       // disables control loop interrupt.  Use this to disable "closed-loop" mode

void antiCoggingCal();            // under development...

void parameterEditmain();         // parameter editing menu

void parameterEditp();            // parameter editing menu

void parameterEditv();            // parameter editing menu

void parameterEdito();            // parameter editing menu

void hybridControl();             // open loop stepping, but corrects for missed steps.  under development

void serialMenu();                // main menu

void sineGen();                   // generates sinusoidal commutation table. you can experiment with other commutation profiles

void stepResponse();              // generates position mode step response in Serial Plotter

void moveRel(float pos_final,int vel_max, int accel);     // Generates trapezoidal motion profile for closed loop position mode

void moveAbs(float pos_final,int vel_max, int accel);     // Generates trapezoidal motion profile for closed loop position mode
```

Examples

Below are a few examples. Please note that there are a few changes from previous versions of the firmware (specifically for the step/dir interface).

Serial Interface

As long as the function `serialCheck()` is included in your loop (it is by default), you can use the built in serial commands. (Full list here.) You can also create your own by creating a function and adding it to `serialCheck()`.

The serial interface is useful for debugging/initial testing. Generally, when using a Mechaduino in a new application, we might do the following:

- Connect to computer, open serial monitor
- Run cal routine, copy table to firmware, recompile, and upload
- Connect Mechaduino to mechanical load
- Set closed loop position mode using commands ‘x’, ‘y’
- Tune PID loop using ‘k’ (parameter edit) and ‘j’ (step response) commands
- Copy best PID values to firmware, recompile, and upload
- Move Mechaduino to various setpoints in closed loop mode using ‘r’ command to test out application

Step/Dir Interface

Here is how to correctly enable the step/dir interface for use with a 3D printer/CNC machine after calibrating and tuning your PID loop.

```
void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);                      // This delay seems to make it easier to establish a connection when the
Mechaduino is configured to start in closed loop mode.
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
  digitalWrite(ledPin,LOW);         // turn LED off

  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

      configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode
}


//////////////////////////////////////
/////////////////LOOP/////////////////
//////////////////////////////////////


void loop()                 // main loop
{

  serialCheck();              //must have this execute in loop for serial commands to function

  //r=0.1125*step_count;        //Don't use this anymore, step interrupts enabled above by
                                //"configureStepDir()", adjust step size in parameters.cpp

}
```

If you would like to use an enable pin, you can uncomment this line:

```
     configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
```

Note that only pins D0 & D1 have built in level converters. You will need to step down a 5V enable signal to 3.3V. You could use a level converter board like this, or a simple resistor divider.

Button

In this code, when digital pin 3 goes HIGH, the Mechaduino moves from 0 to 90 degrees, holds that position for 3 seconds, and then goes back.

```
  void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);                      // This delay seems to make it easier to establish a connection when the
Mechaduino is configured to start in closed loop mode.
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
  digitalWrite(ledPin,LOW);         // turn LED off


  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

  //    configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode

   pinMode(3, INPUT);
}

//////////////////////////////////////
/////////////////LOOP/////////////////
//////////////////////////////////////


void loop()                 // main loop
{
  r = 0;
  if (digitalRead(3) == HIGH){
  r = 90;
  delay(3000);
  }
}
```

Print

Here is some demo code showing how to print some of the the state variables to the serial monitor while the Mechaduino is running. You can access these variables and use them in other ways as well. For example you could toggle some of the GPIO depending on the value of the position error e, or you could set an analog out pin proportional to the control effort u.

```
void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);                      // This delay seems to make it easier to establish a connection when the
Mechaduino is configured to start in closed loop mode.
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
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  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

  //    configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode

}



//////////////////////////////////////
/////////////////LOOP/////////////////
//////////////////////////////////////


void loop()                 // main loop
{
  serialCheck();

  SerialUSB.print("setpoint: ");
  SerialUSB.print(r);
  SerialUSB.print(", error: ");
  SerialUSB.println(e);
  delay(100); //delay 0.1 seconds
}
```

Torque Detect

The Mechaduino can detect and react to external disturbances. In this example, exerting a slight torque in either direction on the Mechaduino's rotor will cause the setpoint to advance in the corresponding direction by 90 degrees:

```
void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);                      // This delay seems to make it easier to establish a connection when the
Mechaduino is configured to start in closed loop mode.
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
  digitalWrite(ledPin,LOW);         // turn LED off


  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

  //    configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode

}

//////////////////////////////////////
/////////////////LOOP/////////////////
//////////////////////////////////////

void loop()                 // main loop
{
  if (u > 35){
    r -= 90;
    delay(100);
  }
  else if (u < -35){
    r += 90;
    delay(100);
  }
}
```

The torque is detected by monitoring the control effort `u` in closed loop position mode.

Slow Moves

By design, setting a setpoint in position mode causes the Mechaduino to snap to the new setpoint as fast as possible. This is not always ideal. There are a number of ways to create slow smooth motion in position mode.

One way is to use an external motion controller to create a trajectory of setpoints for the Mechaduino to follow. An example of this would be using the Mechaduino's step/dir interface with a 3D printer or CNC machine. Here the motion profiles are generated in external firmware/software such as Marlin or Mach 3.

If you would like smooth motion in a stand-alone application, you can generate your motion profile on the Mechaduino itself. To illustrate this, here is a crude loop that will move the Mechaduinos setpoint from 0 to 90 degrees and back at constant speed:

```
void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
  digitalWrite(ledPin,LOW);         // turn LED off

  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

  //    configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode
}

//////////////////////////////////////
/////////////////LOOP/////////////////
//////////////////////////////////////

void loop()                 // main loop
{

  while (r < 90.0){
    r += 0.1;
    delayMicroseconds(100);
  }
  delay(2000);
  while (r > 0.0){
    r -= 0.1;
    delayMicroseconds(100);
  }
  delay(2000);
}
```

We’ve gone a step further and implemented two commands that generate trapezoidal speed trajectories (constant acceleration, max speed, constant deceleration): moveRel() for relative movements; and moveAbs() for absolute movements. From Parameters.cpp:

```
 void moveAbs(float pos_final,int vel_max, int accel){

  //Use this function for slow absolute movements in closed loop position mode
  //
  // This function creates a "trapezoidal speed" trajectory (constant accel, and max speed, constant decel);
  // It works pretty well, but it may not be perfect
  //
  // pos_final is the desired position in degrees
  // vel_max is the max velocity in degrees/second
  // accel is the max accel in degrees/second^2
  //
  //Note that the actual max velocity is limited by the execution speed of all the math below.
  //Adjusting dpos (delta position, or step size) allows you to trade higher speeds for smoother motion
  //Max speed with dpos = 0.225 degrees is about 180 deg/sec
  //Max speed with dpos = 0.45 degrees is about 360 deg/sec
```

And here’s an example showing how to use these functions:

```
 void setup()        // This code runs once at startup
{

  digitalWrite(ledPin,HIGH);        // turn LED on
  setupPins();                      // configure pins
  setupTCInterrupts();              // configure controller interrupt

  SerialUSB.begin(115200);
  delay(3000);
  serialMenu();                     // Prints menu to serial monitor
  setupSPI();                       // Sets up SPI for communicating with encoder
  digitalWrite(ledPin,LOW);         // turn LED off


  // Uncomment the below lines as needed for your application.
  // Leave commented for initial calibration and tuning.

  //    configureStepDir();           // Configures setpoint to be controlled by step/dir interface
  //    configureEnablePin();         // Active low, for use wath RAMPS 1.4 or similar
      enableTCInterrupts();         // uncomment this line to start in closed loop
      mode = 'x';                   // start in position mode
}

//////////////////////////////////////
////////////////LOOP/////////////////
//////////////////////////////////////


void loop()                  // main loop
{
  moveRel(360.0,100, 30);
  delay(2000);
  moveAbs(0.0,100,30);
  delay(2000);
}
```

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