AB MILL
OPERATOR'S MANUAL

Rev: A0424

1 - Safety

Ignorance is dangerous. Read and understand this manual prior to using AB Mill.

The following precautionary statements are used throughout this manual:

Danger: Indicates a hazardous situation that *will* result in death or serious injury.

Warning: Indicates a hazardous situation that *could* result in death or serious injury.

Caution: Indicates a hazardous situation that *could* result in minor or moderate injury.

Notice: Indicates information considered important but not hazard related.

Warning: Crush hazard. AB Mill's gantry and table move with sufficient force to cut metal, and can crush, pinch and tear body parts. Do not reach into AB Mill except as indicated, AND only when the machine is at a complete stop.

Warning: Extremely sharp rotating cutter inside. Secure spindle with wrench prior to servicing cutting tool, following the procedure outlined in this manual.
Caution: AB Mill is computer controlled and can start automatically whenever the USB cable is powered. Keep hands away from all pinch points and cutting surfaces at all times, except as outlined in this manual.

Caution: Never use a dropped, visibly damaged, dull, or suspect cutting tool, as it could shatter. End mills are extremely brittle and should be discarded if dropped, as micro fractures could cause a latent failure while the tool is in motion. Damaged tools can shatter into projectiles without warning.

Caution: The magnetic front entry guard is only intended to contain aluminum chips, and is not designed to contain an improperly secured work piece or shattered end mill.

Caution: Always wear eye and ear protection when operating AB Mill. Do not wear rings, watches, necklaces, loose clothing, or long hair down while operating AB Mill. Wear gloves when handling parts and cleaning aluminum chips, but not while operating the machine.

Caution: AB Mill does not have a dedicated hardware emergency stop button. Unplugging either the USB or power cable will immediately stop AB Mill. The software emergency stop button will only work if AB Mill has a valid USB connection to the host and the host processes the emergency stop command. Due to the indeterminacy of modern operating systems, the software emergency stop button is not guaranteed to stop AB Mill in a reasonable time period, or at all if AB Mill isn't enumerated as a USB device and communicating with the host software.

Caution: AB Mill's spindle and stepper motors generate considerable heat during operation and remain hot for several minutes after unplugging. Prolonged contact with these components could result in minor burn injuries.

Notice: AB Mill is not a consumer device. It is the user's responsibility to operate AB Mill per OSHA 1910.212 - Milling Machine, ANSI B11.8-1983, and OSHA 3067, as amended.

2 - Overview

AB Mill is an open source CNC machine designed to manufacture aluminum objects. Whereas 3D printers additively manufacture objects by depositing material in layers, AB Mill subtractively manufactures objects by cutting material away from pre-existing objects. Subtractive manufacturing is difficult because the machine must accurately determine where the part is - without crashing into it - and remain rigid enough to physically cut away material with specific geometry and tools.

The following table highlights difficulties inherent to subtractive manufacturing:

Difficulty	Additive Manufacturing (3D Printing)	Subtractive Manufacturing (Traditional)	Subtractive Manufacturing (AB Mill w/ .AB file)
Part Mounting	Not required	Vice, expensive jigs	3D printable jigs Contained within .AB file
Initial Geometry	Not required	Required to prevent crashing	Programmed into .AB file
Part Probing	Not required	Separate probe	Cutting tool used as probe Programmed into .AB file
Machine Rigidity	Not required	Heavy frame	Unibody exoskeleton
Cutting Tools	Not required	Various collet systems	ER-11 collet system Step-by-step setup
Tool Path Creation	Simple, Automated	Extensive cutting knowledge	Extensive cutting knowledge Programmed into .AB file
File Distribution	Universal '.stl' format	Job/setup-specific 'g-code'	Distributable '.AB' file

3 - Unboxing

Remove AB Mill and all accessories from the shipping container. Keep the box for future transportation needs; protecting a 50 pound steel chunk is difficult without specific packaging.

Notice: Do not lift AB Mill by the external stepper motors. Applying excessive force to the stepper motors could damage AB Mill's linear accuracy and/or electrical wiring. Lift AB Mill only via the reinforced 1/4" side plates or the machine bottom.

Place AB Mill on a smooth surface in a shop environment conducive to stray aluminum chips. AB Mill must operate in the upright position to prevent chip ingress to sensitive linear components.

Connect AB Mill to a grounded power outlet, then plug AB Mill into a computer with the included USB cable. Place the host computer several feet from AB Mill to prevent stray chip entry.

Warning: To ensure continued safe operation, AB Mill must connect to earth ground via a three-pronged IEC power cord connected to a properly grounded outlet. Defeating the ground protection prong on the included power cable poses an electrocution hazard. In the unlikely event that aluminum chips bridge the input line to the chassis, a properly grounded AB Mill will prevent the outer metal enclosure from energizing by tripping an upstream Ground Fault Circuit Interrupt (GFCI), circuit breaker, or fuse.

Notice: AB Mill produces audible noises when powered and connected to a USB host. This is normal behavior. See FAQ: "Why does AB Mill make noise when the USB cable is plugged in?"

Notice: Connect the power and USB cables in any order.

4 - Software

AB Mill's embedded 328p microcontroller requires the open source Arduino driver for proper enumeration. The simplest method to install the required driver is to run the "install.bat" file included with AB Mill. An alternate method to obtain the driver is to download and install Arduino IDE 1.0.5 or later: http://www.arduino.cc/en/Main/Software

Once the driver is installed, AB Mill is supported in two software environments:

Software	Operating System	Ease-of-Use	Description
ABcut	Windows XP/7/8*	Simple	Automated '.AB' files guide the user through the manufacturing process, including step-by-step instructions with illustrations to setup the part and tools in the machine.
Grbl	MacOS/ Linux/ Windows	Advanced	Manual 'g-code' files are created by experienced users, using concepts not completely described herein. Finished code is packaged into .AB files for distribution to other users, for use with ABcut.

*Mac OS & Linux support are in development, but not initially released.

4.1 - ABcut

ABcut replaces arduous CNC concepts with step-by-step setup instructions and automated milling code. ABcut's simple software interface is solely designed to interpret '.AB' files, allowing users to create predefined objects without part-specific manufacturing knowledge. ABcut doesn't generate .AB files. See "4.3 - Creating .AB Files"for file format requirements.

To simplify part replication, ABcut intentionally lacks many features:

Lacking Feature	Rationale
No g-code command entry line	Automated .AB files don't require manual code entry
No manual jog/spindle control	Automated .AB files don't require manual code entry
No machine coordinate visibility	Users don't need to understand concept
No tool path visualizer	Users don't need to understand concept

4.1.3 - Inspecting .AB Files for Malicious Content

Similar to software viruses, unknown .AB files can reconfigure AB Mill to destroy itself. Such is the nature of open source hardware/software. Before running .AB files on AB Mill, AB recommends simulating the g-code contained within suspect .AB files (e.g. with OpenSCAM, G-code Optimizer, etc). See "4.3 - Creating .AB Files" for specifics on obtaining g-code from within a .AB file.

Watch out for '$' commands that reprogram AB Mill's behavior, including the following:

Command	Example	Behavior
$X	$X	Allows gantry movement without homing, potentially crashing machine
$Nx=command	$N0=$X	Configures a command that runs each time AB Mill connects to the host.
$n=x	$23=0	Modifies Grbl configuration settings, changing machine behavior

The following commands are considered safe

Command	Example	Behavior
$H	$H	homes the machine along Z, then XY axes
$$	$$	Displays Grbl settings
$#	$#	Displays probe, work coordinates and offsets
$G	$G	Displays parser state
$I	$I	Displays build info
$Nn	$N1	Displays stored g-code that runs at startup (should return empty)
$C	$C	Modal g-code status
?	?	Displays current status

See "Appendix A: Supported G-Code Commands" for a complete programming reference. !

Notice: To restore AB Mill's default settings, launch ABcut and run 'DefaultABSettings.AB'.

Hash functions ensure a file isn't modified in transit, assuming the hash publisher is trusted. AB maintains a .AB file hash list at: abmill.net

Users wanting to manufacture preconfigured .AB parts can stop reading the manual here.

4.2 - Grbl

Machinists and designers rejoice: AB Mill uses the (excellent) open source Grbl motion controller, and is 100% hardware and software compatible with that ecosystem's many product offerings. Grbl allows AB Mill to operate as a standard CNC machine, accepting g-code from most CAM post-processors. Rather than introducing yet another generic CNC controller, AB recommends using GrblController or GrblPanel to send gcode to AB Mill.

'Grbl' is often confused with, but isn't:
-GrblController/GrblPanel: GUIs that send g-code to Grbl.
-grblshield (aka 'gshield'): a hardware board that moves stepper motors.
-GrBLDC: a hardware board that controls brushless DC motors.

Grbl users must thoroughly understand the operating principals outlined in this manual. AB Mill has no brain and is entirely capable of destroying itself when programmed incorrectly. Numerous safeguards exist to prevent damage, but in the spirit of open source development, those features are easily modified or disabled.
AB Mill will happily plunge a stationary end mill into a work piece at 30 ipm. If in doubt, ask:
abmill.net

4.3 - Creating .AB Files

The .AB file format simplifies part sharing amongst users. A .AB file is simply a .zip archive with the file extension
changed (for user clarity). A special "manifest.yml" file defines how the file contents are displayed to the user via a series of step-by-step instructions (see "4.3.1 - Creating YAML Files"). A properly designed .AB file houses all manufacturing files and user instructions required to make the contained part:

Housed File Type	Purpose	Required Format
Pictures	Display visual setup	.BMP, .JPG
G-code	Automate machine cutting code	Any ASCII text (extension irrelevant)
3D Printable Jigs	Create jigs, if needed	.STL is most common (extension irrelevant)
Part Model	Allow user to modify part/CAM g-code	Any model file (extension irrelevant)
Guide Files	Supplemental instructions to user, typically PDF.	Any file (extension irrelevant)
Manifest	Defines file presentation order to user.	manifest.yml (lower case)*

*File names are case sensitive inside .zip archives.

Once all files are created (as described in detail below), compress all items into a .zip container, change the file extension from '.zip' to '.AB', and verify the file works as desired in ABcut.

4.3.1 - Creating YAML Files

A root-level "manifest.yml" file defines how ABcut presents each file to the user. The yaml file is editable in a standard text editor, allowing experienced machinists to create .AB files without also requiring a programming background. AB recommends Notepad++ for formatting assistance.

Folders within the .AB file are accessed with forward slashes: `MyCodeFolder/MyAwesomeFile.txt`
Folder and file names within .AB containers are cAsE SeNsItIvE.

Debug tip: Comment out 'step_gcode' commands from manifest.yml to verify the text and images display as intended without actually milling the part.

The manifest.yml file contains the following building blocks:

Syntax*	Description	Example (user text)**
"- job_name: "	A 'job' contains all information required to create a part. Most .AB files make a single part, and thus contain a single 'job'	- job_name: Mill Bottle Opener #At least one job step - job_name: Mill Bottle Opener #At least one job step
"job_text: "	Additional text shown when user selects a job	job_text: Manufacture Bottle Opener
"model_files: "	(optional) One or more files used to: -create a 3D printed jig, and/or -model the part If called, the user can optionally save all files to a user-specified directory, then 3D print and/or modify	model_files: - stl/left_jig.stl - stl/right_jig.stl - stl/part.ipt
"guide_files: "	(optional) One or more files used to provide supplemental information. If called, the user can optionally save all files to a user-specified directory, then access directly	guide_files: - PDF/opener_build.pdf
"job_steps: "	A single list of step-by-step instructions presented to the user to manufacture a part	job_steps: - step_name: Verify Empty step_text: Is AB Empty? step_image: IMAGE/1-Empty.bmp step_gcode: Code/01_Home.txt - step_name: Home step_text: Install nuts.
"step_name: "	Title text summarizing step action	- step_name: Verify Empty
"step_text: "	Bulk text shown to the user during the step. (ASCII text)	step_text: Why was I only created to destroy?
"step_image: "	(optional) Path to image file displayed to user during the step. (.BMP or .JPG)	step_image: IMAGE/1A-Empty.bmp
"step_gcode: "	(optional) Path to g-code file that executes AFTER the user sees 'step_image'/'step_text', then presses next	step_gcode: Code/01_Home.txt
"timeout: "	(optional, step must also contain 'step_gcode') Seconds ABcut waits before returning an error each time AB Mill acknowledges a command. Default is 40 seconds.	timeout: 80
"reset: "	(optional, step must also contain 'step_gcode') After the step completes, AB Mill: False: doesn't reset (default) True: resets, unreferencing the axes	reset: true
"pause: "	(optional, step must also contain 'step_gcode') When 'step_gcode' finishes executing: False: ABcut automatically progresses to the next step (default) True: User must press next to progress to the next step	pause: true

*Note trailing spaces
**Examples assume the .AB file has root-level folders 'stl', 'PDF', 'Code', & 'IMAGE'.
See "Appendix B: YAML Formatting" for complete formatting instructions

Example .AB File:

```
- job_name: Beer Bottle Opener
  job_text: Manufacture an AB Mill beer bottle opener. job_steps:
    - step_name: Verify Empty
      step_text: Is AB Empty?            Verify nothing is installed. step_image: 01_
      Empty.jpg
      step_gcode: 01_Home.nc

    - step_name: Step2#This step doesn't show a picture or execute code.
      step_text: This step only displays this text (it's so meta).

guide_files:                    #file save prompt at job beginning regardless of order
- exampleGuide1.pdf

  model_files:                  #file save prompt at job beginning regardless of order
    - exampleModel1.stl
```

4.3.2 - Creating G-code

Appendix A lists all g-code commands supported by AB Mill.

Some CAM programs generate g-code that moves the cutting tool row-by-row across the part, raising and lowering the Z axis as needed, but otherwise paying no heed to actual part geometry. These programs are suitable for cutting wood and plastic, but do not fare well when cutting metal. AB recommends generating g-code only with CAM programs that cut along part geometry with uniform radial engagement.

The following recommended starting parameters cut 7075-T6 aluminum:

	Rough Slot	Plunge	Drill	Finish	Pocket
Revolutions per Minute	10,000	10,000	6,500	10,000	10,000
Method	Trochoidal Climb	Helical Climb	Peck	Conventional	Trochoidal Climb
Feed rate (mm/min), or Ramp angle (°)	750	75	2.5	380	380
Depth of Cut (mm)	3.175	-	2.5	3.0	3.8
Step over (mm)	0.375	-	-	0.200	0.300

25.4 mm equals 1 inch

4.3.3 - Creating 3D Printable Jigs

Distributing subtractively-manufactured designs is traditionally difficult due to the various fixtures, clamping tools, and/or vices required for each design and available to each user. 3D printing attempts to overcome these obstacles by enabling each user to reliably reproduce the exact jigs used to secure a particular part, even if that part isn't rectangular. 3D printed jigs abstract alignment concepts from the user, enabling automated machine alignment to the part.

3D printed jigs must hold the work piece rigid to prevent cutting vibration. Plastics are weak when tensioned, torqued, or sheared, but remain rigid when compressed. Thus, jigs should attempt to contact as much surface area as possible between the part and T-slot. Apply compression with bolts, but make sure neither the bolts nor the T- slot contact the part if using the integral probe; see "5.6 - Using the Probe".

5 - Hardware

AB Mill is a three-axis desktop subtractive manufacturing machine primarily designed to cut aluminum and other soft, non-ferrous metals. The machine can also cut plastic, wood, and other soft materials. AB Mill is **not** designed to cut steel, titanium, or other hard metals. Skilled machinists attempting to cut hard metals must use small cutters to prevent overloading AB Mill's limited power, torque and rigidity limits. AB Mill lacks a lubrication system, which is required when cutting most hard metals.

AB Mill's unibody steel exoskeleton increases rigidity per unit weight, but AB Mill is certainly less rigid than an 800 pound industrial machine. Understanding that AB Mill - like all CNC machines - will flex proportional to an applied load is paramount to understanding its ultimate cutting abilities. While an 8000 pound machine might 3" inch face aluminum at 0.150" DOC, AB Mill would require several passes with a much smaller cutter and less DOC to achieve the same task. As a hobbyist CNC machine, AB Mill's part throughput is less critical than cost.

5.1 - Referencing the Machine

AB Mill prohibits motion until the machine is referenced (a.k.a 'homed') to a limit switch on each axis. Software limits are then used to prevent out-of-bounds motion that could damage the machine. Tools 3" or less can remain installed while referencing. Remove tools over 3" before homing, as they won't clear the T-slot plate. Parts can remain installed while referencing as long as they don't interfere with the fully retracted tool.

'$H' initiates the referencing routine, which first retracts Z, then simultaneously moves the T-slot plate up and the spindle right. Each axis is them pulled 1 mm from its limit switch. Grbl operates all three axes in negative space (i.e. quadrant III operation). Once referenced, the software origin (0,0,0) is at the machine's bottom (X+), right (Y+), and rear (Z+). However, since the limit switches are located at X-/Y+/Z+, the machine position immediately after homing is (-74,-1, -1).

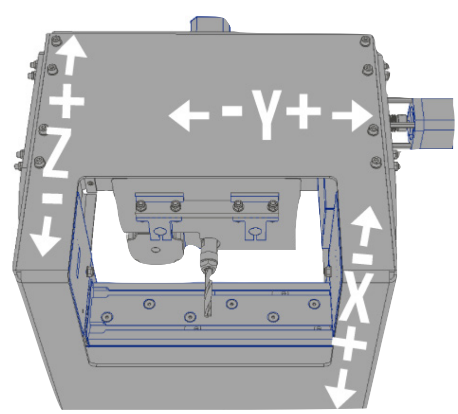
5.2 - Understanding the Work Coordinate System

AB Mill is designed to cut holes much deeper than most hobbyist CNC machines. AB Mill uses a horizontal spindle to prevent chip accumulation in deep pockets. The horizontal spindle also increases 3D printed jig rigidity. All three axes operate in negative coordinate space and follow standard right hand rule nomenclature:

Axis	Absolute Range (mm)	Recommended Range* (mm)	Limit Switch Location (mm)	Positive command physically moves...	Positive command (as seen by part) moves...
Z	-60.5 <= Z <= 0	-60.5 <= Z <= -0.2	Z = 0	...tool away	...tool away
Y	-140 <= Y <= 0	-140 <= Y <= -0.2	Y = 0	...tool right	...tool right
X	-75 <= X <= 0	-74.8 <= X <= 0	X = -75	...T-slot down	...tool up

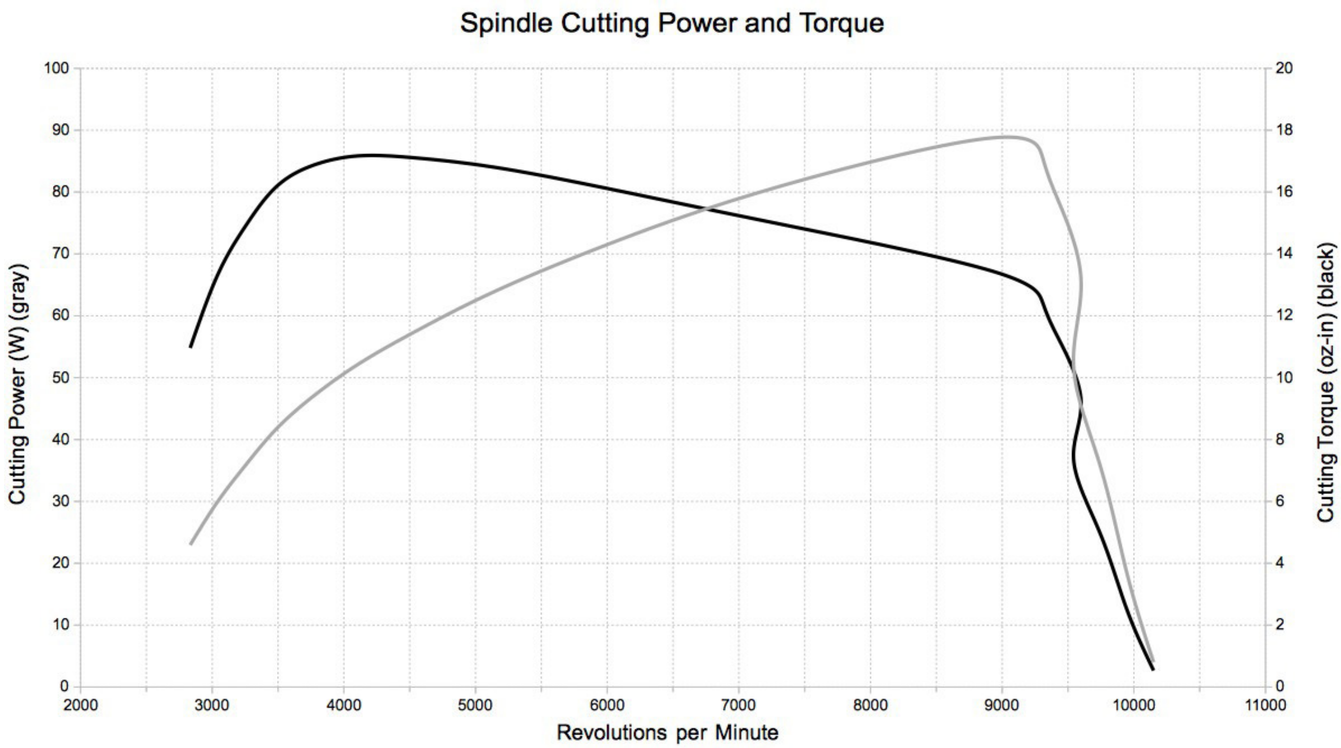
**Maintain a gap to prevent accidental limit switch tripping.*

The figure at right shows physical axes movement. The Y & Z axes physically move in the same direction as seen by the part. However, the X axis physically moves in the opposite direction than is seen by the part. The direction shown in the figure at right is the physical direction the T-slot will move.
Appendix C contains larger labels that attach to the machine.



5.3 - Spindle Operation

AB Mill's custom-designed spindle operates between 4,000 and 10,000 rpm via a closed-loop current- limited PWM signal. Spindle speed is constant unless the cutting bit is loaded beyond AB Mill's torque and/ or power capabilities. Typical mechanical cutting power and torque curves are shown below:



Observation	Rationale
AB Mill has considerably less power and torque than professional CNC machines	Professional machines deliver kW+ cutting power and foot-pound+ cutting torque
AB Mill's optimal speed is 7,000-9,000 rpm	Maximum power delivered at 9,000 rpm
Cutting below 4,000 rpm isn't recommended	Cutting torque decreases below 4,000 rpm
AB Mill rapidly loses cutting power and torque above 9,000 rpm	Back-EMF = Vin at 10,400 rpm, at which point no additional energy enters the system.
Set spindle speed to 10,000 rpm to mill aluminum, but assume speed is 9,000 rpm for speed calculations	Cutting torque rapidly drops above 9,300 rpm
Spindle won't rotate below 2,800 rpm	Motor doesn't turn

The spindle requires a five minute warmup period at full speed to warm the bearings prior to cutting. Attempting to mill before the spindle is warm could trip AB Mill's overcurrent circuitry, as the spindle itself consumes significant power until reaching operating temperature. The following example code properly warms the spindle:

```
M3 S5000      (start motor)
G4 P1         (pause 1 second for speed) S10000      (set
motor full speed)
G4 P300       (wait 5 minutes.          Note timeout period requirements)
```

Caution: The spindle operates at elevated temperatures and remains hot long after operation ceases. Do not directly touch the spindle subassembly for at least 15 minutes following any cutting operation.

5.3.1 - Spindle g-code

AB Mill supports the following spindle g-code commands:

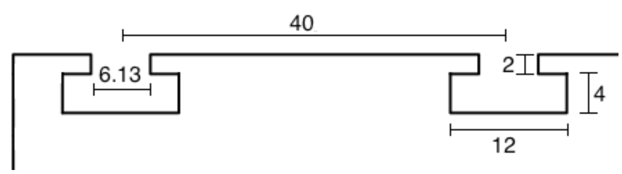
Command	Example	Behavior
M3	M3	Rotate spindle clockwise
M4	M4	Rotate spindle counterclockwise
M5	M5	Stop spindle
Sn	S10000	Run spindle at speed 0 <= *n* <= *10000*

Full scale spindle speed/direction changes can trip AB Mill's overcurrent protection circuitry. For example, an instantaneous request to stop a spindle operating at 10,000 rpm requires the controller to short all three phases out, generating a massive overcurrent condition. AB Mill will lose reference if the X/Y/Z axes are moving when an overcurrent condition occurs. The following example code limits current when stopping the spindle:

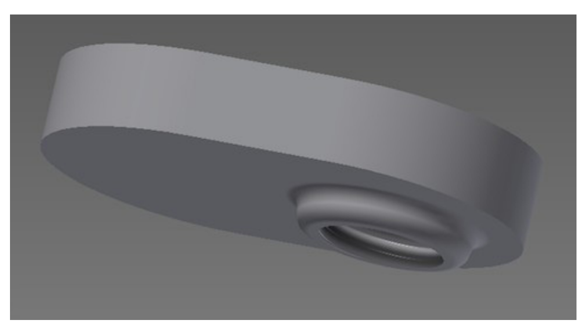
```
M3          (Turn spindle CW.          Spindle won't spin until 'S' is set)
S5000       (Run spindle at half speed)
G4 P1       (Pause for one second to allow spindle to speed up) S10000     (Run spindle at
full speed)
G4 P2       (Wait for spindle to reach full speed before cutting) (Cutting code)
S5000       (Slow down spindle)
G4 P1       (Pause for one second to allow spindle to slow down)
S0          (Set spindle to 0 rpm)
M5          (Stop spindle)
```

5.4 - Installing a Work Piece

AB Mill's mounting plate consists of two T-slot rails spaced 40mm apart. The T slot rail dimensions are compatible with industry standard 20mm T-nuts. AB recommends at least three mounting points when possible to reduce chatter. Two mounting points are acceptable if the mounting jig has sufficient width and an alignment groove, to prevent part walking during milling.



Each T-slot rail has an opening on the left side to accept T-nuts. Insert T-nuts bump-side down (shown at right).

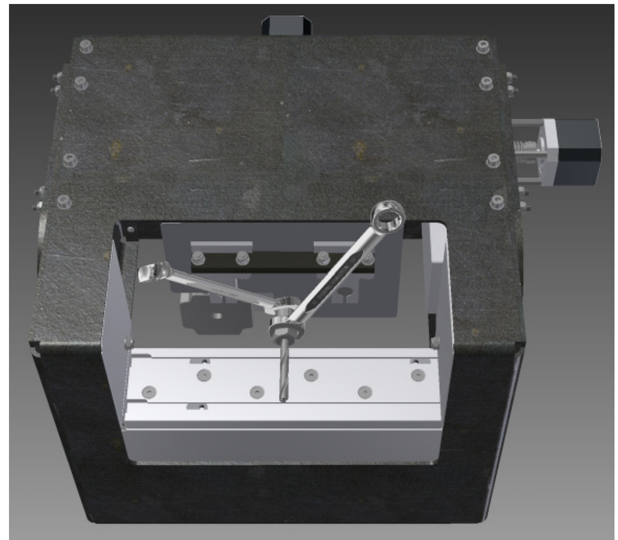


Caution*: Loose work pieces are projectiles when struck by a high speed end mill. Ensure your work piece is securely fastened prior to milling.*

Notice: Loose work pieces dull end mills.

5.5 - Installing/Changing Tools

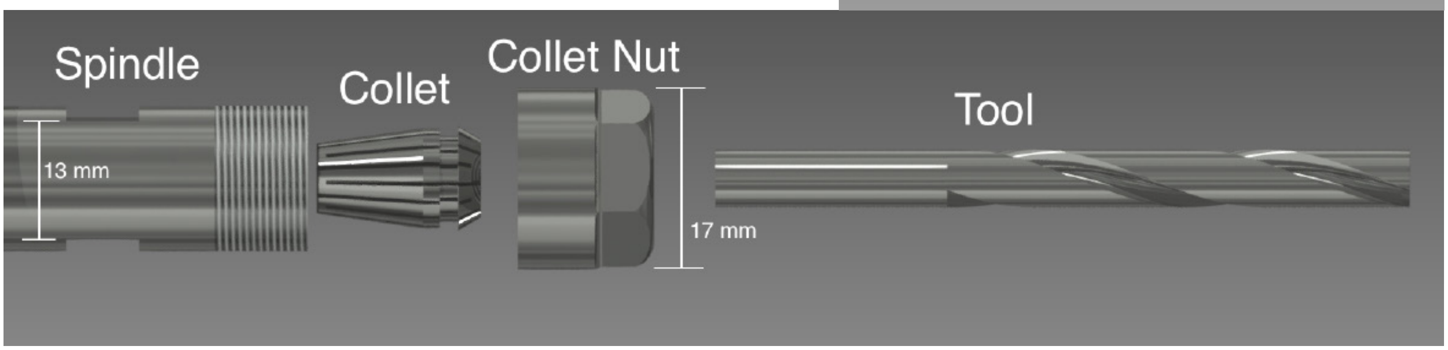
AB Mill accepts industry standard ER11 collets.
Follow these instructions to change tools:



A). Remove the work piece, if required.

B). Center the Y axis and plunge the Z axis.
Example code:

```
G90            (absolute position)
G21            (mm units)
G53 G0 Z-1     (Retract Z)
G53 G0 X-1     (Move table down)
G53 G0 Y-70    (Center Y axis)
G53 G0 Z-60    (Plunge Z axis)
```



C). Place a 13 mm wrench onto the spindle's spanner slot. Due to the spindle's low torque, holding the wrench in place prevents spinning if accidentally enabled.

> *Caution: If the spindle enables while the 13mm wrench is installed - but not retained in hand - then the wrench could become a projectile.*

D). Place a 17mm wrench onto the collet nut.

E). While holding the 13mm wrench stationary, force the 17mm wrench counterclockwise, thus loosening the collet nut. Apply the force from one tool to the other, not directly into the spindle's mechanical frame. The nut will initially loosen, then tighten again. Keep turning the collet nut counterclockwise until it loosens again.

F). Remove the existing tool.

G). Remove the collet nut and verify the collet is clean. Aluminum chips inside the collet reduce gripping force and increase runout.

H). If the replacement tool diameter differs from the existing tool, push the collet at an angle to remove it from the nut, then press the new collet into the nut until it clicks.

I). Screw the collet nut a few turns onto the spindle, then insert the new tool into the collet. If the tool's shank is greater than 1", slide the tool in as far as possible. Don't fully insert a tool if the shank is less than 1", as the collet is only designed to crimp a solid cylindrical surface.

J). Tighten the collet by holding the 13mm wrench stationary while turning the 17mm wrench clockwise. Keep tightening the nut until it is VERY tight. The ER11 collet is sufficiently tight at 30 foot pounds of applied torque, but unless you have a torque wrench, this number is useless; it is difficult to over tighten the collet nut. Loose nuts allow the tool to walk while milling, which will ruin your work piece, your tool, and possibly your machine.

K). Remove the 17mm wrench, then remove the 13mm wrench.

5.6 - Using the Probe

AB Mill includes a built-in probe to zero the part to the machine. To use the probe, connect the red cable to the part, then mount the part to the T-slot with an electrically isolated jig. The probe won't work if the part electrically contacts the T-slot plate, hence the use of 3D printed mounting jigs.

The probe command returns X/Y/Z coordinates when the (grounded) tool contacts the (5 V) part. AB Mill supports G38.2 probing (probe toward workpiece, stop on contact, error if no contact). G38.3/4/5 isn't supported.

Example probing code:

```
S3000           (spindle set to 3000 rpm)
M3              (turn spindle clockwise)
G91             (relative movement)
G21             (mm units)
G38.2 Y-10 F40  (probe Y axis up to -10 mm at 40 mm/min)
                (Grbl returns X/Y/Z position)
G10 L20 P2 Y2.5 (zero Y axis to tool center, assuming 5 mm diameter)
```

The last line merits further explanation:

Command	As used in example	General Description	General Syntax
G10	Set Work Coordinate System	Set Work Coordinate System	G10
P2	Use WCS G55*	P1 through P6 correspond to WCS G54 through G59, respectively	P*n* 1<=*n*<=6
Y2.5	A 5mm tool contacts the part 2.5 mm from tool center (sign changes depending on probe direction)	One or more axes to set (X/Y/Z). Only called axes are set	X*n* and/or Y*n* and/or Z*n* *n* is a positive or negative number within machine limits
L20	Set current position of Y axis of WCS G55 to 2.5 mm	Set current position of specified axis of specified WCS to specified value.	L20

*Work coordinates are persistent until explicitly changed, even after power-cycling.

The following table summarizes potential probing outcomes:

Probe cable status when probe command issued	Result	Hardware Outcome	Software Outcome	$V_{part\text{-}to\text{-}T\text{-}slot}$
Connected to part and isolated from T-slot	Probed correctly	Tool contacts part and stops	Correct zero determined	4.5 to 5.5 V
Disconnected from part and floating.	Tool contact with part undetected (probe remains high)	Tool stalls or mills into part until reaching user-specified maximum probing distance	Error, probe didn't contact part. Reset required	0 V
Shorted to T-slot (due to chips, mounting, etc)	Ground short detected	No movement occurs	Error, probe is shorted to ground. Reset required	0 V
Connected to part and isolated from T-slot, but tool too far from part	Tool never contacts part	Tool moves to user-specified maximum probing distance	Error, probe didn't contact part. Reset required	4.5 to 5.5 V
Connected to part and isolated from T-slot, but spindle rpm too fast	Tool contact time to part insufficient to trip probe.	Tool cuts aluminum until either tripping or reaching user-specified maximum probing distance	Incorrect zero determined (if probe trips), or error (if probe never trips)	4.5 to 5.5 V

*Measuring the voltage between the part and T-slot can uncover setup issues.

The spindle must rotate while probing. A stationary tool's contact radius isn't constant because stationary tools aren't cylindrical. However, the probe circuit won't trip if the spindle rotates too fast, due to a 110 kHz low pass filter that prevents false tripping. Most metal cutting tools probe best around 3000 rpm. There's typically no advantage to probing at higher rpm, except that anodized (aluminum oxide) part surfaces aren't conductive, and thus the probe must tear through that thin layer to contact the conductive aluminum below (dull tools will take longer). AB recommends lightly sanding away anodization at each contact surface prior to probing.

The spindle is turning too fast if the end mill eats into an aluminum part before the probe trips; a properly configured probe is sensitive enough to only microscopically cut the part before tripping. In fact, when properly configured, repeated probing in the same location doesn't introduce appreciable zero drift. Use the equations below to determine maximum probing rpm:

CalculationE	quationE	xample* at 10000 rpm	Example* at 3000 rpm
Tool Contact Percentage	$\frac{Contact\ Circumference}{Tool\ Circumference}$	$\frac{0.140"}{0.250"} = 56\%$	$\frac{0.140"}{0.250"} = 56\%$
Contact Percentage per Tooth	$\frac{Tool\ Contact\ Percentage}{Number\ of\ Teeth}$	$\frac{56\%}{2\ teeth} = 28\%$	$\frac{56\%}{2\ teeth} = 28\%$
Single Tooth Contact Time	$\frac{Contact\ Percentage\ per\ Tooth}{revolutions\ per\ minute}$	$\frac{28\%}{10000\ rpm} = 28\ us$	$\frac{28\%}{3000\ rpm} = 93\ us$
Minimum contact time met?	Single Tooth Contact Time > 50us?N	oY	es

*Example uses the Destiny Viper 0.250" end mill (included with AB Mill).

It's probably a given, but the probe doesn't work on nonconductive parts. Traditional X/Y/Z touch-off methods are of course supported - paper snagging, roller gauges, etc - but they're not automated. One possible nonmetallic probing method is to connect the probe cable to adhesive aluminum tape mounted on three surfaces (X/Y/Z). We leave these implementations to the traditional machinist, as AB Mill's primary focus is automated aluminum machining. AB advises creators to distribute aluminum parts to casual users, as the probe functionality is a vital simplification tool to inexperienced users.

5.7 - Electrical Overview

AB Mill contains the following power rails:

Rail	Source	Subsystems powered
24 V	Wall-powered AC->DC converter	Stepper motors, BLDC spindle motor, cooling fan
5 V	USB host	Limit switches, 328p uC, all I/O logic, motion control signals, probe

AB Mill immediately ceases all motion if either rail is unpowered (i.e. the USB and/or power cables are disconnected). The machine loses zero if move commands are sent while the 24 V rail is unpowered; the software-calculated position will update, but the motors won't actually move. The host doesn't know whether the 24 V rail is powered. AB Mill's hardware can detect whether 24 V is present (via 328p pin A4), but that feature isn't presently implemented in software.

Notice: To prevent crashing due to lost steps, immediately unplug the USB cable if move commands are issued while the 24 V rail is unpowered. Reference AB Mill prior to resuming movement.

AB Mill contains three current-limiting circuits:

System Monitored	Reasons Monitored	Method	Result	Reset Required if Current Limit Hit?
Spindle	Limits RMS current! Prevents overheating	Spindle PWM reduced	Spindle slows down until within current limit	No
Steppers	Motors are current controlled devices	Potentiometers control constant current source	Steppers pull constant current	No
24 V Rail	Short circuit (di/dt) Overcurrent (Imax)	Rail temporarily disabled	24 V rail hiccups*	Yes

As a safety feature, the following events will temporarily disable the 24 V rail:
-Aluminum chips short the 24 V rail to ground (the entire 24 V system is guarded from chips)
-Spindle stalls due to incorrect programming or incorrectly installed work piece
-Spindle starts or stops too quickly (see "5.3.1 - Spindle g-code" for proper coding technique)
-The cutting tool is dull/broken.

> *Notice: If the spindle stalls for any reason during a cutting operation, immediately stop milling by unplugging the USB cable and assume the machine is no longer referenced.*

*When an overcurrent event occurs, the 24 V rail turns off due to overcurrent, remains off for several seconds,
then turns back on. The cycle repeats if the overcurrent condition persists. If the overcurrent event is due to spindle inrush current, either set the spindle speed to 0 rpm ('S0'), or unplug the USB cable.
During an overcurrent event:
-the fan stops spinning
-the spindle stops spinning (if spinning)
-stepper motors stop moving (if moving)

AB Mill is controlled by three PCBs:

PCB	Function	Firmware	More Information
328p Uno-R3 compatible microcontroller, running Grbl	-Communicates with host -Interprets g-code -Plans stepper motion -Responds to probe -Responds to limit switches -Sends stepper pulses to gShield -Generates spindle PWM signal	Grbl 0.9g, PWM spindle control enabled*	github.com/grbl/grbl
gShield	-Drives X/Y/Z stepper motors	n/a	github.com/synthetos/grblShield/wiki
GrBLDC	-Drives spindle BLDC motor -Filters probe noise -Filters limit switch noise -Isolates gShield noise from 328p -Fan/probe/limit connections	n/a	abmill.net

*GrBLDC requires Grbl's compile-time-configured PWM-spindle pinout, which flips two pins to utilize a PWM output normally occupied by a limit switch. See Grbl's documentation for detailed information.

6 - Maintenance

Like most industrial machinery, AB Mill requires periodic maintenance. With proper care, AB Mill should remain operational for many years. Some maintenance requires axes realignment to ensure the machine is square. AB Mill might not operate correctly if the machine isn't properly aligned.

6.1 - Removing Chip Accumulation:

Routine vacuuming is the most important preventative maintenance. If allowed to accumulate, chips can work past guards and then contact the sensitive linear rails and ball screws, reducing bearing life. Chips rapidly accumulate while cutting; aluminum chips occupy approximately 15 times more space than the uncut solid. ! To simplify cleanup, AB Mill lacks a lower panel. After milling, temporarily move the machine to another location, then vacuum up aluminum chips. Vacuum inside the machine via the front entry access. Once most chips are removed, tilt AB Mill left to gain additional vacuuming access. The goal is to vacuum away as many chips as possible to prevent contamination into sensitive components.

Notice: Do not use compressed air to clean AB Mill. AB Mill's sensitive components are gravity-sealed from aluminum chips. Blowing air into AB Mill will force chips past the sealed areas into sensitive components, decreasing AB Mill's useful life. !

Notice: Inverting AB Mill prior to cleaning could allow chips to bypass gravity seals and contact sensitive components. Thoroughly vacuum AB Mill prior to inverting, shipping, or servicing.

6.2 - Protection from Rust

AB Mill incorporates aluminum, steel, and stainless steel parts:

Material	Protection Method	Example Parts
Aluminum	Inherent, aluminum corrodes to stronger aluminum oxide	Shaft Supports NEMA mounts T-slot
Stainless steel	Chromium passivation	Spindle Bearings
Powder coated steel	Coating prevents oxygen from contacting steel	Enclosure Plates
Chrome plated steel	Chromium passivation	Shafts, ball screws
Black oxide bolts	Oil-impregnated conversion coating	Bolts
Chromoly steel	None	Y flange bearing housings Spindle outer tube

A few steel parts are unprotected from oxidation and will develop cosmetic rust if stored in a humid environment. Parts with surface rust treatments will also oxidize if said treatment is compromised. As with other industrial machinery, periodically applying a thin layer of oil will prevent cosmetic surface rust. Operate AB Mill in a climate controlled environment and prevent sudden temperature changes to reduce water condensate exposure.

6.3 - Leveling X Axis

The X axis is driven by two stepper motors and can unlevel when the machine is crashed hard; one stepper loses steps, but not the other. The following example routine verifies the X axis is level:

Command	Description
G90 G21 G55	Absolute mm movement in WCS G55
G53 G0 Y-70 X0	Position X & Y for 1/4” end mill installation
G53 G0 Z-60	Plunge Z, then install 1/4” end mill
G53 Y-0.5	Move Y axis to machine right
	Place a sheet of paper between tool and T-slot
G91 G0 X-0.1	Move X stage towards tool (relative) (Repeat command until paper snags)
G10 L20 P2 X0	Zero X
G91 G0 X+3	Move X away from table (to prevent crash if unleveled)
G53 G90 G0 Y-140	Move Y axis to machine left
G91 G0 X-0.1	Move X stage towards tool (relative) (Repeat command until paper snags)
$#	Display WCS. Adjustment not required if -0.1 <= *X* <= 0.1 mm

X axis leveling is required if *X* exceeds ± 0.1 mm.

<u>If X>0.1 mm (e.g. X = 0.5 mm):</u>
Unplug the power cable, then rotate the left ball screw until the tool barely snags the paper. The left ballscrew is accessed by slightly tilting AB Mill. Verify the X axis is level by rerunning the above routine.

<u>If X<-0.1 mm (e.g. X = -0.5 mm):</u>
Move the Y axis right (‘G53 G0 Y-0.5’), unplug the power cable, then rotate the right ball screw until the tool barely snags the paper. The right ballscrew is accessed by slightly tilting AB Mill. Verify the X axis is level by rerunning the above routine.

Notice: The Y & Z axes only use one stepper motor; leveling isn’t required on those axes

6.3.1 - Unbinding X Axis

The X axis can bind if enough steps are lost during a crash, or if the machine is dropped or bent. If the axis binds:
A). Unplug the power.
B). Turn the X ball screws until they rotate smoothly. Smooth rotation should occur when the T-slot is perpendicular to the X shafts.
C). Perform the “Leveling X Axis” procedure

If binding persists, contact AB for further guidance, or to create an RMA.

6.4 - Resolving a Tripped Limit Switch

AB Mill enters an alarm state when a limit switch trips, preventing all movement, including referencing. Tripped limit switches typically indicate something catastrophic occurred. ABcut checks for tripped limit switches each time the software launches, and will automatically move the X/Y/Z axes as needed to resolve the error condition.

To manually resolve a tripped limit switch:

Command	Description
	Determine which limit switch is tripped.*
Ctrl-x	Soft reset Grbl (ASCII code 24), or unplug and reconnect USB
$X	Unlock AB Mill**
$20=0	Disable Soft Limits***
Ctrl-x	Soft reset Grbl (ASCII code 24), or unplug and reconnect USB
$X	Unlock AB Mill
G91	Relative Movement
G21	mm (Units)
G0 X+1 or G0 Y-1 or G0 Z-1	Move away from limit switch on tripped axis. Moving an axis closer to a tripped limit switch will destroy it.
Ctrl-x	Soft reset Grbl (ASCII code 24)****
$20=1	Enable Soft Limits
Ctrl-x	Soft reset Grbl (ASCII code 24), or unplug and reconnect USB
$H	Home machine.

*An LED on each limit switch illuminates when tripped. Limit switches are located:

Limit Switch	Mounting Location	Switch Contacts	LED Visible
X	Enclosure (behind right X ballscrew)	X plate (front right corner)	Between T-slot and right inner chip cover
Y	Y plate (bottom right)	Enclosure (right side)	Between gantry and right inner enclosure
Z	Y plate (rear center)	Z ballscrew mount (rear)	Above spindle when viewed at a low angle

***Allows movement without referencing. The machine remains unlocked for the remainder of the session.*

****Soft limits prevent positive absolute movement (outside quadrant III), even when the machine is unlocked.*

*****Another reset is required because limit switches activate both when pressed AND when their state changes.*

7 - FAQ

Q: Why does AB Mill make noise when the USB cable is plugged in?
The stepper motors that position the X/Y/Z axes use microstepping to increase positioning resolution. Microstepping uses two high current PWM waveforms to place the motor between two discrete phases. PWM waveforms are variable frequency square waves. Square waves are mathematically infinite sinusoidal sums, resulting in audible noise. To remove the noise (not recommended and an advanced modification):
-Disable microstepping by placing jumpers across all six 0.1” gshield headers
-Change each axis’ “steps/mm” parameter to 50 (i.e. “$100=50”,”$101=50”, “$102=50”)

Q: Why won’t the X stage move?
See “6.3.1 - Unbinding X Axis”.

Q: Why does AB Mill keep starting and stopping?
If the machine is running known-good g-code, verify the tool isn’t worn out. As the parts wear, more energy is required to perform the same cutting task. See “5.7 - Electrical Overview” for more information on how a dull tool can trip the overcurrent safety feature. With proper care, the consumable end mill and drill that ship with AB Mill should manufacture numerous parts, but will eventually require replacement.

Q: Why did AB Mill crash into the part while probing?
See “5.6 - Using the Probe” to verify the probe is properly connected.

Q: Why won’t AB Mill respond to motion commands?
Make sure the power cable is plugged in and the fan is spinning. If AB Mill still doesn’t move, see “6.4 - Resolving a Tripped Limit Switch”.

Q: Why won’t AB Mill work?
In the spirit of open source, AB encourages users to diagnose, troubleshoot and improve the machine as a community: abmill.net. To obtain service, contact AB as described in the “RMA Policy”.

Q: Why does spindle motor pitch change during warmup?
Bearings are conceptually simple, but are actually incredibly complicated. AB Mill’s spindle uses heavily preloaded, press-fit angular contact bearings to reduce runout. When the spindle is cold, nonuniform grease viscosity and metal constriction intermittently combine to require more power than AB Mill’s currentlimited PWM feedback loop is programmed to deliver. As the bearings heat, the metal expands and grease viscosity decreases, thus decreasing power lost as friction. Human ears are incredibly sensitive to pitch changes, but assuming the spindle is used within specification, the actual RPM value changes very little (less than 5%).

Q: How is spindle power measured?
Most manufacturers list their machine’s peak power consumption, which occurs only when power is first applied to a stationary motor. This figure is typically MUCH higher than the motor’s actual rated continuous power consumption. For example, a certain ‘300 W’ spindle used in other machines overheats in under 15 minutes if continuously loaded to 75 W using a dynamometer. AB Mill’s specified power is the continuous cutting energy transferable to the work piece, as measured by a dynamometer.

Q: Why are there two X stepper motors?
AB Mill’s horizontal spindle configuration doesn’t allow a single, central linear X drive; the screw would punch through the build platform. Placing a single drive screw at one edge reduces the other edge’s rigidity. Thus, two ball screws are required (one at each edge).

Q: Why are there two stepper motors sticking outside the machine?
AB Mill’s mechanical rigidity is derived from its compact, single-piece enclosure. Increasing the enclosure dimensions (to encompass the Y & Z stepper motors) exponentially decreases overall rigidity. Note these motors aren’t handles and are easily damaged. Also note the pinch points on either side of the Y (rear) stepper.

Q: Are nonconductive jigs required to mill parts?
To use the probe, the mounting method must not allow the part to conduct to the T-slot. 3D printed jigs are easy to design and can secure nearly any part geometry, allowing probe use and distribution within .AB files.

Q: Why are all specifications metric? This is America!
The metric system is nearly universally adopted because it's better, namely when converting between units (e.g. 1000 mg = 1 g = 0.001 kg). Now that Myanmar has initiated metrication, only Liberia and America are standardized to the Imperial system. Interestingly, America attempted Metrication 40 years ago, but the citizens stubbornly refused to accept the charge.

Q: Where is AB Mill's serial number?
Serial numbers permit regulatory abuse. AB Mill doesn't have a serial number, but the Uno-R3 board contained within it does: the unique, read-only serial number cannot be erased. AB retains this serial number to determine when a particular machine was manufactured, but no other personally identifiable information is linked to that number. Certain universal identifying marks exist to verify a particular machine was manufactured by AB.

Q: How open source is AB Mill?

A full list of hardware and software sub-licenses is available on the USB flash drive that ships with AB Mill.

Q: How is AB Mill Assembled?
AB advises against disassembling AB Mill unless required; proper axes alignment requires considerable time and effort.

8 - RMA Policy

This RMA Policy applies to all customer requests for Return Merchandise Authorization (RMA), and is in addition to those found in the AB Mill Terms and Conditions of Sale (Terms of Sale). The Terms of Sale take precedence and supersede this RMA Policy.

AB may modify this RMA Policy at its sole discretion from time to time. The most recent RMA Policy is available at: abmill.net

AB will not accept any product for service or repair without prior authorization, as evidenced by an RMA Number. To receive an RMA Number, a Customer must:

- -Request an RMA Application Form by emailing support@abmill.net, and
- -Fully complete the RMA Application Form to receive an RMA Number, and
- -Include the completed RMA Application Form with all returned product, and
- -Write the RMA Number on the outside of all shipping containers used to return product.

Non-functional/defective peripherals are considered separate items and are treated as a separate RMA. Customer must only send nonfunctional products as described in the RMA Application Form used to create the RMA Number. Do not return functional peripherals unless requested by AB.

An RMA Number is valid for sixty (60) days from issuance, at which time said RMA Number expires and is void; AB must receive the returned product under said RMA Number within this sixty (60) day period.

AB IS NOT OBLIGATED TO ACCEPT ANY RETURNED PRODUCT not in compliance with AB's RMA Policy. SUCH PRODUCT MAY BE returned to CUSTOMER freight collect.

DO NOT SEND FIREARMS TO AB. AB is not licensed to accept firearms sent via courier, per 18 U.S.C. 922(a)(3) and 922(a)(1)(A). AB will legally dispose any received firearms.

AB products are sold without warranty. AB charges a flat $200 Service Charge that covers all parts and labor required to replace materials deemed defective through normal use. AB may, at its discretion and on a case-bycase basis, offer to waive some or all incurred Service Charges. RMA repair work is not warrantied.

AB's RMA Department will notify Customer prior to charging more than the Service Charge and will provide Customer with an estimate regarding the cost of such service. AB reserves the right to charge the Customer for parts, labor, and shipping expenses if AB determines that:

- -Consumable components returned with product require replacement, or
- -The cause for RMA was: misuse, abuse, alteration, improper installation, incorrect repair, negligence in use, improper handling, or inadequate protection during transportation by any party other than AB, or
- -The customer intensionally misrepresented information on the RMA Application Form to make it appear that the product required RMA due to normal use, or
- -No defect is found.

If no defect is found, AB will attempt to contact the Customer to obtain additional information to reproduce the defect. If AB is unable to obtain further Customer information to reproduce the defect, AB will assume the product is operating correctly and will return it without aABitional testing.

AB expects to ship serviced or repaired products within thirty (30) business days of receipt (Turn Around Time). This Turn Around Time is an estimate; failure to repair or replace the product within Turn Around Time does not breach this RMA Policy.

AB shall not be liable for any delay in performance directly or indirectly caused by or resulting from acts of nature, fire, flood, accident, riot, war, government intervention, embargoes, strikes, labor difficulties, equipment failure, late deliveries by suppliers, or other difficulties which are beyond the control and without the fault or gross negligence of AB.

9 - Specifications

Parameter	Value	Unit	Note
X/Y/Z travel	75/140/60.5	mm	-
X/Y/Z table size	125/230/95	mm	Larger X and Z dimensions possible depending on part geometry
Spindle Cutting Power	115	W	Irms limited
Spindle speed	3000-10000	rpm	Variable
Input Voltage	90-250	Vac	-
Input Frequency	45-70	Hz	Sinusoidal
Weight	22	Kg	~49 pounds
Shipping Weight	25	Kg	~55 pounds
T-slot spacing	40	mm	Center-to-center
Table T-slots	2	QTY	Compatible with 20 mm T-nuts
Collet system	ER11	-	Accepts tools up to 8 mm
Operating temperature	0-40	°C	To prevent overheating
Relative Humidity	0-50	%	To reduce oxidation
Max linear velocity	28	mm/s	Simultaneous X/Y/Z Traverse
Max single-axis velocity	16	mm/s	Software-limited
5 V current (max)	95	mA	Can plug into unpowered hubs
24 V current (max)	155	W	For 10 minutes
24 V current (continuous)	120	W	-

Appendix A: Supported G-Code Commands

Supported g-code command summary (less used commands in gray):

Command	Example	Name	Summary
Fn	F10	Feed Rate	Set maximum velocity on speed-limited commands. Unit = G20/21
G0	G0 X-2 Y-1	Rapid Move	Move as fast as possible in a straight line to the specified point
G1	G1 X-2 F1	Linear Move	Move at specified Feed Rate in a straight line to the specified point
G2	search online	CW Arc	Arc at specified Feed Rate in specified plane
G3	search online	CCW Arc	Arc at specified Feed Rate in specified plane
G4	G4 P2	Dwell	Pause for specified period (seconds)
G10 L2	G10 P2 L2 X1	Set WCS point	*P1:P6 indicates which WCS - G54:G59 - to modify, respectively.* Set specified WCS axes to specified value based on machine absolute origin, without movement (current position ignored). *Example sets WCS G55's X axis 1 unit from machine absolute zero*
G10 L20	G10 P2 L20 X1	Set WCS point	*P1:P6 indicates which WCS - G54:G59 - to modify, respectively.* Set specified WCS axes so current position becomes specified value, without movement. Use to set WCS based on probed result. *Example sets current X position to 1 in WCS G55*
G17	G17	Set XY Plane	Sets arc plane to XY
G18	G18	Set XZ Plane	Sets arc plane to XZ
G19	G19	Set YZ Plane	Sets arc plane to YZ
G20	G20	Unit = inch	Set units to inches. Persists until G21 is called, or reset.
G21	G21	Unit = mm	Set units to mm. Persists until G20 is called, default on reset.
G28	G28 Z-1	Move to G28.1 via axes	Move to specified position (in current WCS), then move to absolute position stored in G28.1. *Example moves to Z-1 in the current WCS, then moves to G28.1*
G28.1	G28.1	Store final G28 position	Store the current absolute position, for use by G28
G30	G30 Z-1	Move to G30.1 via axes	Move to specified position (in current WCS), then move to absolute position stored in G30.1 Example moves to Z-1 in the current WCS, then moves to G30.1
G30.1	G30.1	Store final G30 position	Store the current absolute position, for use by G30
G38.2	G38.2 X-2 F5	Probe	Probe towards part, stop on contact, error if no contact
G53	G53 G0 X-2	Use Machine origin	Move in machine coordinates, regardless of active WCS. G53 only applies to code on the same line (not persistent)
G54 G55 G56 G57 G58 G59	G55 X-2	Work Offsets 'WCS'	Work offsets define an origin in relation to absolute machine zero. Work offsets are persistent, Use the origin defined in the specified work coordinate system (persistent). See 'G10' to define the origin. Example moves 2 units from origin defined by WCS G55

Command	Example	Name	Summary
G90	G90 X-2	Absolute Move	Move relative to current WCS. *Example moves 2 units from origin*
G91	G91 X-2	Relative Move	Move relative to current position. *Example moves X axis 2 units*
G92	G92 X0Y0Z1	Coordinate Offset	*Source of epic misery, do not use; use WCS instead.* Set active WCS position as specified (without movement). Modifies all WCS axes to match calculated offset. Unspecified axes aren't modified. Not stored in EEPROM, cleared when reset. *Example sets active WCS origin Z+1 from current position and modifies all WCS axes to match calculated offset.*
G92.1	G92.1	Clear Offset	Clear previously set G92 coordinate offset.
G93	G93	Minutes/Unit	F interpreted as inverse feed rate
G94	G94	Units/Minute	F interpreted as feed rate
M3	M3	Spindle CW	Spin spindle CW at specified speed
M4	M4 S5000	Spindle CCW	Spin spindle CCW at specified speed
M5	M5	Stop Spindle	Stop the spindle, as specified in "Spindle Operation"
M8	M8	Enable Coolant	AB Mill supports coolant, but no system is installed
M9	M9	Disable Coolant	AB Mill supports coolant, but no system is installed
M30	M30	End	End program. Before calling M30, stop spindle as per "Spindle Operation"
M100 Un	M100 X10	Verify Remaining Travel	(Supported in ABcut only) Verify at least *n* distance is available on *U* axis between last probe point and absolute machine limit. Alarm if *n* exceeds available distance on *U* axis. Error if no probe has occurred. M100 disregards unit mode; all arguments are in mm
M101 Vm	M101 X1	Verify Delta Between Points	(Supported in ABcut only) Verify distance between the two most recent G38.2 probe results is less than *m* along axis *V*. Alarm if calculated delta exceeds *m*. Error if less than two previous probe operations have occurred. M101 disregards unit mode; all arguments are in mm.
Sn	S5000	Spindle Speed	Set the spindle speed, as specified in "Spindle Operation"

More Grbl-specific command information:
http://www.shapeoko.com/wiki/index.php/G-Code !

Grbl attempts to follow LinuxCNC's g-code syntax and methodologies:
http://linuxcnc.org/docs/html/gcode/gcode.html !

Grbl configuration commands:
https://github.com/grbl/grbl/wiki/Configuring-Grbl-v0.9

Appendix B: YAML Formatting

YAML is a new-line-separated, space-delimited format:

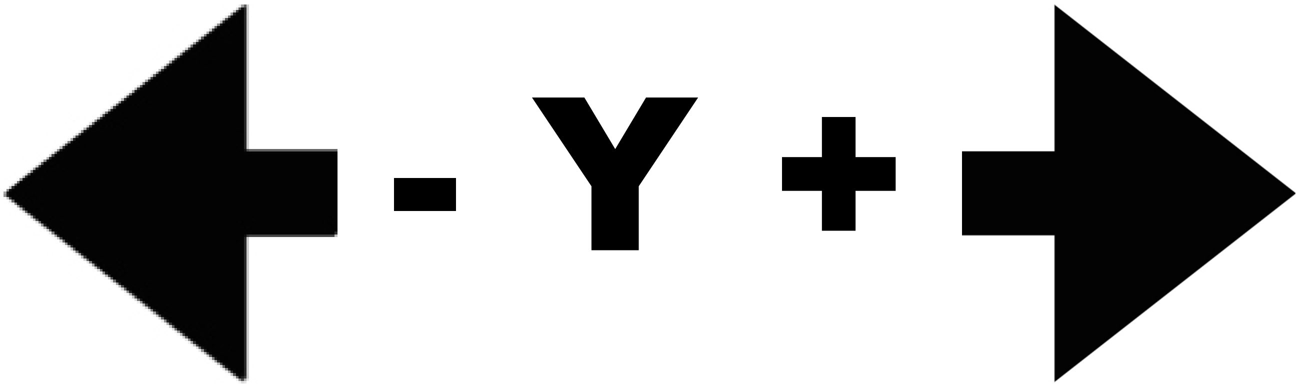
Description	Example
Subsequent lines are Children if space-indented further than the Parent line	Parent: Child: NotChild:
Text following the pound symbol ('#') is a Comment	#Comment
Strings are simple text data. Indicate a new line with "\n"	This is a string\nThis is on a new line
Arrays are groups of named values	red: (value) green: (value) blue: (value)
Lists are a group of values indicated with a "- " *(Note a space follows the dash)*	- (value) - (value) - (value)

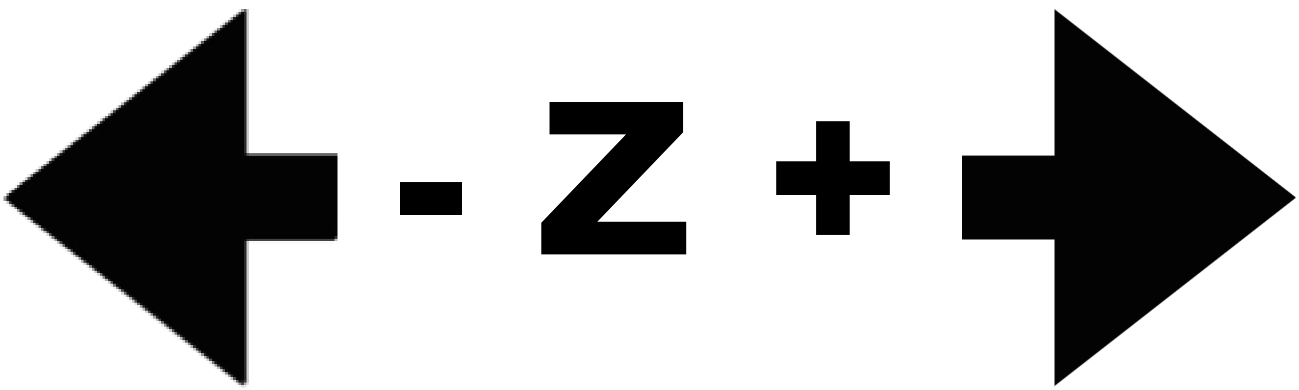
List and Array items may have String, Array, or List Children	name1: this is a string value\nthis text is on a new line name2: #a comment is placed here
	  child1: (value) child2:
	  (value) child3: (value)
	name3:
	  - (value)
	  - (value)
	  - (value)

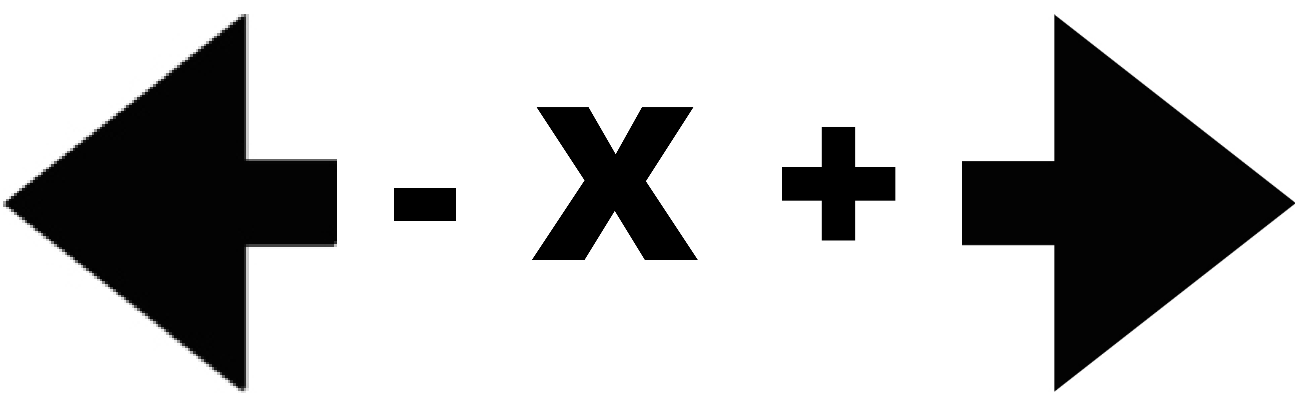
Children of String, Array and List items are allowed.
 	
Lists of lists aren't allowed
	- this is a string value\nthis text is on a new line
	- child1: (value) child2:
	  (value) child3: (value)
	#note a list of lists is never used in the manifest
	- - (value)
	  - (value)
	  - (value)

Appendix C: Individual Axis Labels

Section “5.2 - Understanding the Work Coordinate System” creates an axis movement reference. If desired, cut out these larger labels and tape them to AB Mill.







Physical T-slot Movement