Machine calibration

Note: In order for the controllers to process any action not starting with "M", or for a controller other than the main one to process any command sent from the main controller, they have to be unlocked (a locked device will have an "ssf" value of 128 or 129 in the controller printouts in the terminal). Issue "M511" to each controller to toggle its locked state. This can be done from the main controller by prepending ">id" to the command, where "id" is the id of the target controller.

I. Controller id assignment:

1. Before starting please download and install the serial terminal of your choice (YAT is a good one: https://sourceforge.net/projects/y-a-terminal/).
2. Connect the machine to a computer using a serial cable and turn the machine on.
3. Open your serial terminal and connect to the machine using the appropriate serial COM port name.
4. When the machine is powered on for the first time, each controller will have a random id assigned to it. In general, this should be changed in the interest of predictability. **It's best to assign id 0 last and to the main controller (the one connected to the computer)**, since the COPIS client depends on it. This controller will ideally be the first or last in the chamber so that id assignment can be successive. **For example: if the computer is connected to the first controller in the top chamber, that controller would be assigned id 0 (assigned last), the next one would be id 1 and the third controller would be id 2. Then replicate this front-to-back pattern in the bottom chamber with ids 3, 4 and 5.**
5. Note that when assigning ids it's best to plug into each controller individually and issue command "M101Vid" where "id" is the id number being assigned. **It's also best to assign id 0 last.**
   Alternatively, id assignment can be done while connected to the main controller. The steps to achieve this are as follows:
   - Turn the machine on. All controllers should have a random id and be set as secondary devices.
   - Set the main controller as primary by issuing "M101" (this can be issued on any controller to toggle its primary status). After that, issuing "M120" (this only works on the primary controller) should scan for other controllers on the bus and report it in the terminal.
   - Verify that the other controllers (other than the main controller) on the bus are set to secondary by issuing "M503Vid" where "id" is the number identifying the target controller. That id is visible in the terminal for each controller after issuing "M120". Look for the entry "Is Primary: 0" in the controller settings printout, which indicates that the device is not the primary device.
   - In order to visually match a controller to an id, issue a small pan command with the id (e.g.: ">25G0P10" if id = 25) and take note of which gantry moved. Note, if

the target you are trying to move is locked, you will need to issue >idM511 (where id is the target controller) to unlock it.
- Issue ">[current-id]M101V[new-id]" in the sequence described in step 4, with 0 being assigned last to the main controller. In this command "current-id" is the controller's currently assigned id and "new-id" is the id we are assigning to it. Issue ">[old-id]M998" to reboot the target controller using its old address.
- **Note: after issuing that command to each controller, power the entire machine off for 10 seconds then back on for the id reassignment to be reflected at the main controller.**
- Power the machine off and on, then it'll be ready for use.

II. Camera leveling (repeat the following steps for each camera):

1. To ensure that the camera is leveled, use the onboard sensor features. We will describe this process which applies to the Canon EOS 80D and Canon EOS RP.
2. Ensure that the machine is on and connect to a computer with a serial terminal open and connected.
3. Manually pan and tilt the pan/tilt assembly to its designated 0 position. If the camera cradle resists movement, the motors may be engaged. The motors can be disengaged by issuing command "M18".
4. After positioning the pan/tilt assembly, engage the motors to ensure the assembly is locked in place by issuing command "M17".
5. Connect to the camera via USB, open the Canon EOS utility software (download for Canon at https://www.usa.canon.com/support/eos-utilities), and open live-view for the connected camera.
6. The video should display a single red line, meaning that it is horizontally leveled. If not, intersecting blue and red lines will be visible. The red line indicates the horizontal reference and the blue line indicates the sensors offset relative to the reference. The goal is to adjust the cradle until the 2 lines overlap and only the red line is visible.
7. This is done by loosening the screws on the inside of the cradle (left and right side) and adjusting each side up and down until the sensor is leveled. The Camera itself may need to be loosened from the cradle and twisted to access the screws.
8. After horizontal leveling is achieved, tighten the screws back up, twist the camera back into a straight line as much as possible and fasten to the cradle firmly but not tightly; minute adjustment will be made to it later on.

III. Top chamber:

1. P (pan) axis calibration (applies to bottom chamber as well):
    a. If more than one gantry is present on the same Y axis, manually slide each gantry along the Y axis so they are at least XXmm apart.

b. Manually slide the front gantry along the X axis so that it is clear of the sides of the frame (We'll assume the front gantry in the top chamber is your main controller).
c. Issue pan-homing command "G28P" to home the pan/tilt assembly. The assembly will stop once it hits the pan limit switch; most likely not at the desired "0" position. Put the controller in relative movement mode by issuing "G91" and jog the pan axis until you've reached the desired 0 degree position. This is done by repetitively issuing "G0P10", for example (rotate clockwise by 10 decimal degrees) until 0 is reached. Fractional angular values can be issued (e.g.: .05 decimal degrees) for fine tuning.
Note: depending on where the assembly stopped, negative angular values might need to be issued to rotate counterclockwise toward 0. Make sure to rotate along the shortest path to 0.
d. Once the pan/tilt assembly is at 0, issue home-offset command "M428P" to save the offset, so that it will persist across power cycles.
e. Repeat steps b through d for the other gantries. Make sure to prepend ">id" to each command, where "id" is the controller assigned id number. This is optional if USB/Serial is connected to the main controller (which is typically defined as Zero).
Note: Don't forget to reset the controllers to absolute move more by issuing "G90".
f. Once calibrated in this manner, issuing "G28P" to a gantry should cause it to home to the limit switch then automatically pan to its configured 0 position.

2. T (tilt) axis calibration (applies to bottom chamber as well):
a. Ensure the gantries and pan/tilt assemblies are still away from each other and the frame.
b. Issue tilt-homing command "G28T" to home the pan/tilt assembly on the main controller. The assembly will stop once it hits the tilt limit switch; most likely not at the designated 0 position.
c. Jog the tilt in a similar fashion to the pan in step 1.c: issue relative move command "G91" then jog with "G0T10". Note the "T" for: tilt 10 decimal degrees up. Issue negative numbers to tilt down.
d. Once the pan/tilt assembly is at 0, issue home-offset command "M428T" to save the offset, so that it will persist across power cycles.
e. Repeat steps b through d for the other gantries. Make sure to prepend ">id" to each command, where "id" is the controller assigned id number. This is optional if USB/Serial is connected to the main controller (which is typically defined as Zero).
Note:Don't forget to reset the controllers to absolute movement mode by issuing "G90".
f. Once calibrated in this manner, issuing "G28T" to a gantry should cause it to home to the limit switch then automatically tilt to its configured0 position.

3. Z (height) axis calibration:
    a. Ensure the gantries are still away from each other and the frame.
    b. Issue command “G28Z” to home the Z axis on each gantry. All cameras will now be at their lowest position (default Z position of 0).
    c. Next, we need to ensure that each camera’s sensor references the same coordinate space along the Z axis. To achieve this, pan each camera pair to face each other and determine which is highest: pan the front and middle ones and jog them close; note the higher camera. Do the same for the middle and back ones, and you should be able to determine the highest of all three. The determination can be visual (looking at the lens rims), or the cameras can be turned on and their respective electronic level line can be compared.
    d. Once the highest camera has been determined, we’ll add home offsets to the lower ones to bring them all to the same frame of reference. To achieve this, adjust the highest camera and its neighboring camera to face each other. Jog the lower camera to match the higher one’s height, then issue home-offset command “M428Z” to save the Z offset. Repeat for any remaining uncalibrated cameras.
    e. These steps also apply to the bottom chamber, except that cameras are homed upward and should be offset to the lowest one.
4. Y (depth) axis calibration (applies to bottom chamber as well):
    a. Ensure the gantries are still away from each other and the frame.
    b. Additionally, stagger each Z/pan/tilt assembly so they are apart from each other along the Y axis.
    c. Issue command “G0Zn” to each camera, where “n” is the desired maximum height (300 is a good number to start with. The Z axis can then be jogged by smaller increments for fine tuning, Note that you’d preferably want to reach as high as possible without the pan motor jamming against hardware above it, and call that your maximum height).
    d. Issue depth-homing command “G28Y” to the first camera.
    e. Repeat homing command for each successive camera in order from front to back.
    f. Mark the position of one of the last gantry’s bottom wheels clamping the Y rail. Let’s choose the bottom right wheel and call this mark M1.
    g. Mark the position of the bottom right wheel on the middle gantry. Let’s call this mark M2.
    h. Jog the last gantry as far back as possible without hitting the frame (even when panning). Make a note of the distance traveled. Let’s call it A.
    i. Jog the middle gantry far enough past the M1 to allow enough space for the front gantry.
    j. Jog the front gantry to M2 so that its bottom right wheel aligns with it in the same manner as the middle gantry’s did; as exactly as possible.

k. Note the travel distance. Let's call it B. This will serve as the transient Y home offset for the middle gantry. **Transient here means that it'll apply until overwritten or until the controller/machine is power cycled.**
l. Jog the front gantry to M1 so that its bottom right wheel aligns with it in the same manner as the back gantry's did; as exactly as possible.
m. Note the travel distance. Let's call it C. This will serve as the transient Y home offset for the back gantry.
n. Add distances A and C. This will be the maximum allowable distance on the Y axis. Divide that number by 2 to obtain the distance to the middle of the Y axis. Let's call it D. So the Y axis range will be from -D to +D.
o. Home the front gantry, then issue command "G0YD". Mark the position of the bottom right wheel on the front gantry. Let's call this mark M3. This is the middle of the Y axis.
p. Home Y for all the gantries as before and verify that they all go to D when sent to "0". To do this:
    i. Issue "G92Y-D" to the front gantry to set its transient Y offset (and lower Y (depth) bound.
    ii. Issue "G92Y- B" to the middle gantry to set its transient Y offset.
    iii. Issue "G92Y-C" to the back gantry to set its transient Y offset.
    iv. Issue "G0Y0" to the back gantry to send it to the middle of the Y axis. Its bottom right wheel should align with M3. Then issue "G0YD" to send it to the upper Y (depth) bound.
    v. Issue "G0Y0" to the middle gantry to send it to the middle of the Y axis. Its bottom right wheel should align with M3. Then issue "G0Yn" where n is a sufficient distance to allow the front gantry to be positioned over M3
    vi. Issue "G0Y0" to the front gantry to send it to the middle of the Y axis. Its bottom right wheel should align with M3.
q. Issue "G0Y-D" to send the front gantry back to the lower Y (depth) bound.

5. X (width) axis calibration (applies to bottom chamber as well):
    a. Issue "G0Y" to send the middle gantry back to the middle of Y.
    b. Issue width-homing command "G28X" to home the middle gantry.
    c. Jog it as far as possible to the opposite side without hitting the frame (even when panning). This travel distance will be your maximum allowable X.
    d. Divide it by 2 and let's call that value E. Your X range will be -E to E.
    e. Home X on the middle gantry again, then issue "G92XE" to set its transient X offset (and upper X (width) bound).
    f. Issue "G0X0" to send the middle camera to the middle of the X axis.
    g. Pan it to 0 ("G0P0") and tilt it to look straight down ("G0T-90"). Lower it (e.g.: G0Z100) a bit, for more accuracy.
    h. Turn the camera on, and through your viewing method of choice (LCD monitor or PC utility), affix a marker onto the chamber floor, centered in

the camera shot, with crosshairs lined up with the X and Y axes. This is the chamber's X/Y axis center that all cameras will reference.

i. Set this reference point for each remaining camera in the chamber:
    i. Position the camera over the middle of the Y axis (M3).
    ii. Home its X axis, and point the camera down in the same manner as the middle camera.
    iii. Jog the camera to the center and record the distance traveled. This distance will be the absolute value for each bound of the X range for this camera.

6. Z-to-floor offset (applies to bottom chamber as well):
    a. When the cameras are at their lowest (highest for bottom chamber cameras) position, and if mounted as to not breach the X/Y plane between the 2 chambers, the Z offset from that position and the center of the chamber needs to be computed so that it can be accounted for during path generation. We use the pythagorean theorem for this.
    b. We will position each camera at 4 corners of a square (or rectangle) at height 0 around the chamber and compute the length of the side opposite the tilt angle necessary for the camera to look at the center. That length will be our Z offset.
    c. Each camera will be placed, in turn at:
        i. G0X150Y0Z0P90T0
        ii. G0X-150Y0Z0P-90T0
        iii. G0X0Y100Z0P0T0
        iv. G0X0Y-100Z0P180T0
    d. At each of those positions, turn the camera on and target the center of the X/Y plane (the crosshairs mark from before), ensuring that the camera's electronic level line passes through the intersection of the crosshairs.
    e. Take note of the tilt angle $\boldsymbol{\theta}$. Then calculate the Z offset $\boldsymbol{\beta}$ using the formula: $\boldsymbol{\beta}$ = tan($\boldsymbol{\theta}$) * $\boldsymbol{\alpha}$, with $\boldsymbol{\alpha}$ being the $\boldsymbol{\theta}$'s adjacent side (non-zero X or Y value at that position.)
    f. For each camera, sum the absolute values of $\boldsymbol{\beta}$ at each corner and divide by 4 to obtain an average offset. Apply the appropriate sign (+/-) to the offset depending on the direction of Z movement (top cameras rise into positive values from 0, bottom cameras lower into negative values from z) and set it as the lower bound for Z in the machine profile (COPISClient) and the minimum/maximum Z value in controller's firmware:
        i. Issue "M209Z$\boldsymbol{\beta}$" to set min Z value for cameras in the top chamber.
        ii. Issue "M208Z$\boldsymbol{\beta}$" to set max Z value for cameras in the bottom chamber.

7. Homing Sequence

">2G28ZF700\n>1G28ZF700\nG28ZF700**n>2G92Z88.71\n>1G92Z93.05\nG92Z96.46\n>2G1Z388.71F700\n>1G1Z393.05F700\nG1Z396.46F700**\nG28YF200

0**nG92Y-408.4**\nG28XF2000**nG92X344.8****nG1X-344F2000**\n>1G28XF2000**n>1G92X344**\n>1G28YF2000**n>1G92Y-276****n>1G1X0F2000**\n>2G28XF2000**n>2G92X342.75**\n>2G28YF2000**n>2G92Y-137.6**\n>2G28PTF800\n>1G28PTF800\nG28PTF800"

">2G28ZF700\n>1G28ZF700\nG28ZF700**n>2G92Z96.88****n>1G92Z95.09****nG92Z87.60****n>2G1Z396.88F700****n>1G1Z395.09F700****nG1Z387.60F700**\nG28YF2000**nG92Y-402**\nG28XF2000**nG92X337.5****nG1X-337.5F2000**\n>1G28XF2000**n>1G92X345**\n>1G28YF2000**n>1G92Y-263****n>1G1X0F2000**\n>2G28XF2000**n>2G92X338.5**\n>2G28YF2000**n>2G92Y-128**\n>2G28PTF800\n>1G28PTF800\nG28PTF800"