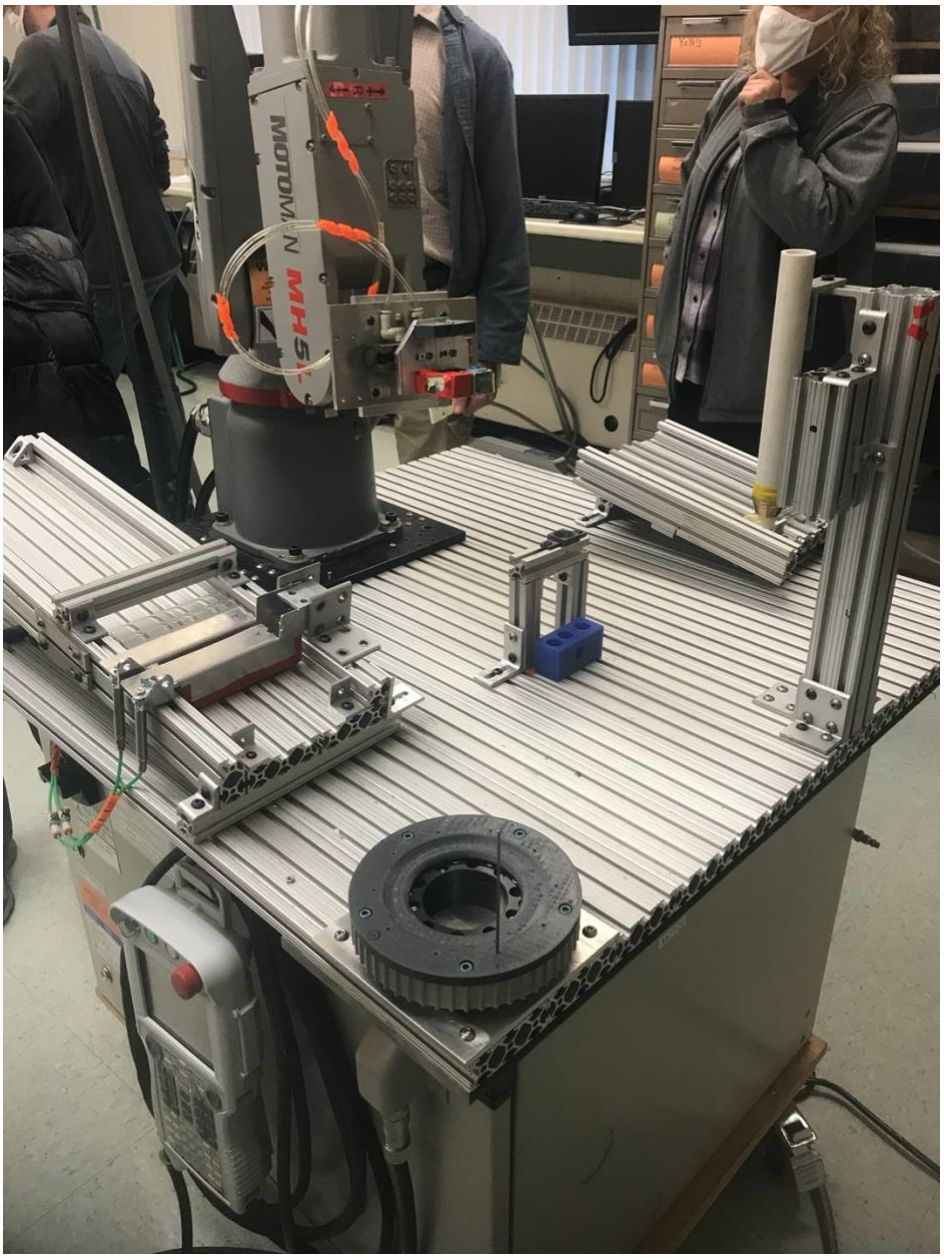
Robotic Manufacturing of Vascular Repair Samples



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Overview

Parts:

- **MOTO**MAN MH5L
- **MOTO**MAN Mounting Plate
- Assembly Mounting Plate
- Gripping Assembly
    - Parallel Pneumatic Grip (Robohand)
    - Aluminum Mounting Plates (x2)
    - 3-D Printed Grips for Mandrel (x2)
    - 3-D Printed Grips for Glass Tubes (x2)
- 3-D Printed Mount for Mandrels on Turret
- Delivery Tube for Silicon Plugs
- Pneumatically Actuated Arms for Glass Tube Delivery (x2)
- 3-D Printed Assembly Base
- Delivery Base

Software:

- **MOTO**MAN Robotic Software

Compressed Air

Description of Function

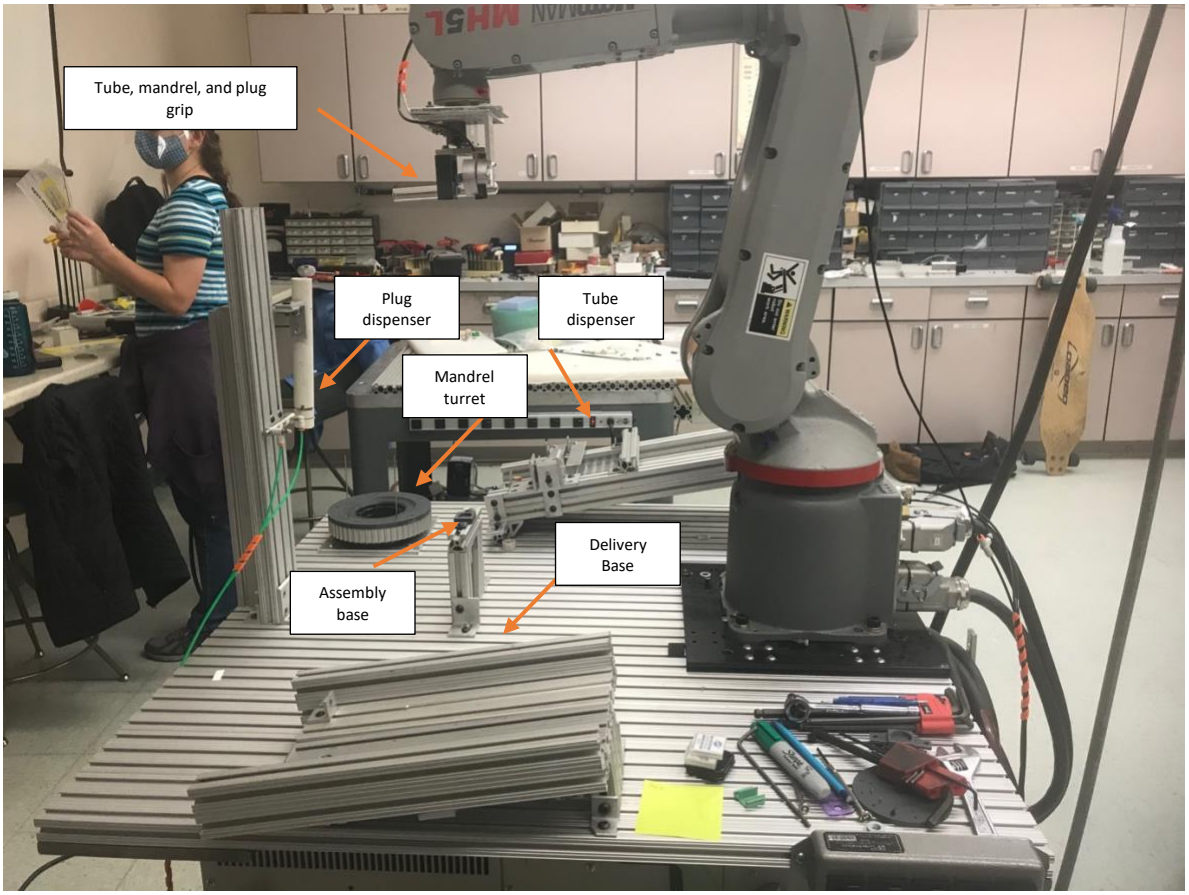
The function of the automated assembly is to pull together three individual items needed to build and secure a bio-printed vascular graft sample, for the repair of vascular tissue, and prepare it into a ready-to-ship form. The assembly system takes each individual item, the plug, the mandrel, and the tube, and assembles them at a centralized assembly station before they are delivered to the dispenser to head off for packaging.

Instructions

1. Ensure that your supply of glass tubes, mandrels, and plugs are properly loaded and that the mandrel indexing turret is properly aligned.
    a. Plugs should be loaded with the flange facing the top of the entry of the tube. This allows the narrow end of the plug to come out of the dispenser, but not fall out
    b. Glass Tubes are loaded with the open end of the tube facing the center of the table, or away from the foam padded side of the dispensing tray. An entire culture tube box can be placed upside down with a slot cut in the box to allow a large number of tubes to be staged at once.
    c. Load mandrels into the labeled holes 1-. Line up the marker arrows underneath the turret to match on both the turret and the turret base.

2. Starting the MOTOMAN
    a. Ensure the MOTOMAN is plugged into the wall socket.
    b. Flip the large power switch (found on the base below the culture tube loading ramp) and allow it to fully boot (its progress can be found on the MOTOMAN remote).
    c. Attach the light-grey compressed-air hose to the air filter found on the base beneath the assembled tube delivery base.
    d. Make sure that the emergency stop is released from the robot controller
3. Loading the program
    a. Once booted, navigate to the main menu on the display
    b. Tap Jobs and navigate on the screen to “Project_Silicone_1”
    c. Hit the “Enter” key to open “Project_Silicone_1”
    d. Switch the key to “Play” mode
    e. Press the large green physical “Start” button at top of the remote
    f. Start the program again and repeat the process until the number of desired vascular graft tubes are fully assembled
4. During Operation
    a. For continuous operation, make sure to either load or have a constantly fed supply of mandrels, plugs, and tubes
    b. One mandrel should be added each time after the robot indexes the mandrel turret
5. Jams
    a. Tubes may turn sideways in loading compartment: correct before continuing to run the robot
    b. Plugs may get caught sideways inside the feeding compartment: straightening the bottom plug should fix this
    c. The assembled test tube may not roll completely down the ramp or may roll down crooked. While the robot is running or stopped, adjust the assembled tubes so that they line up to prevent further jams.

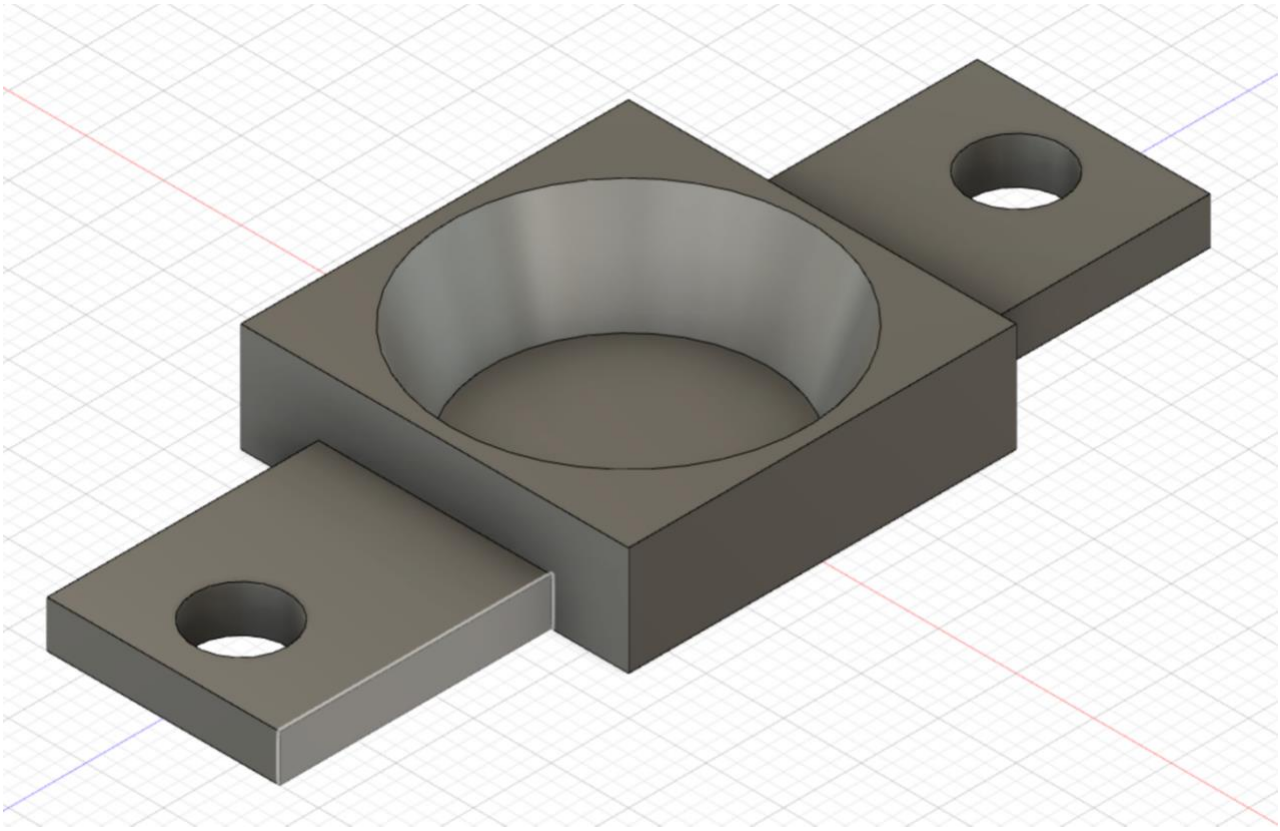
Station Diagram



Description of Setup

Assembly Base

The assembly base was a 3D-printed base elevated on aluminum bars to accommodate for the motion allowed by the motion limitations of the MOTOMAN robot arm. The base is designed to comfortably fit and secure the silicone plug with the top flange in the bottom of the base. There is a taper in the base to guide the plug to the bottom while holding it secure particularly when the mandrel or the tube are being attached to it.



CAD Model of Assembly Base

Plug Dispenser

The plug dispensing station consists of a gravity-fed tube for loading the silicone plugs with a tapered piece connected at the bottom. The tapered piece prevents the plugs from falling out on their own and works as a cup dispenser. The robot grabs the plug from the dispenser, then places it in a pocket in the 3D-printed assembly base. This pocket holds the plug upright and in one spot.

Mandrel Turret

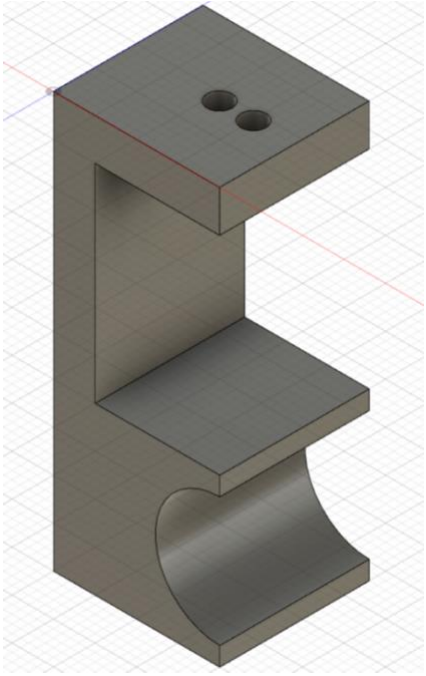
The mandrel turret consists of a sloughing bearing with a 3D-printed mount to hold the mandrels. The sloughing bearing is mounted on an aluminum plate that can be moved to anywhere in the work area. A 3D-printed mount is secured on top of the sloughing bearing and contains holes for placement of the mandrels. During operation, the robot grabs the mandrel at its base, then uses the mandrel to rotate the bearing to get ready for when it needs to grab the next mandrel. The robot then pulls the mandrel straight up before moving to insert it into the plug.

Test Tube Dispenser

The test tube dispenser is made of several different parts. The main piece is a tray made from aluminum where you would be able to place the box of test tubes. It is set at an angle to allow gravity feeding of the tubes. Two pneumatically controlled gates prevent tubes from rolling down on their own. The gates are spaced just wide enough apart to fit one tube between them. Under normal operation, the test tubes would feed out from the box and roll down the tray before being stopped at the first gate. To separate the tubes, the first gate is opened, allowing one tube through. After the first gate shuts, the second one opens, letting the tube enter the robot work area. The robot is now able to pick up the single tube and place it over the preassembled mandrel and silicone plug.

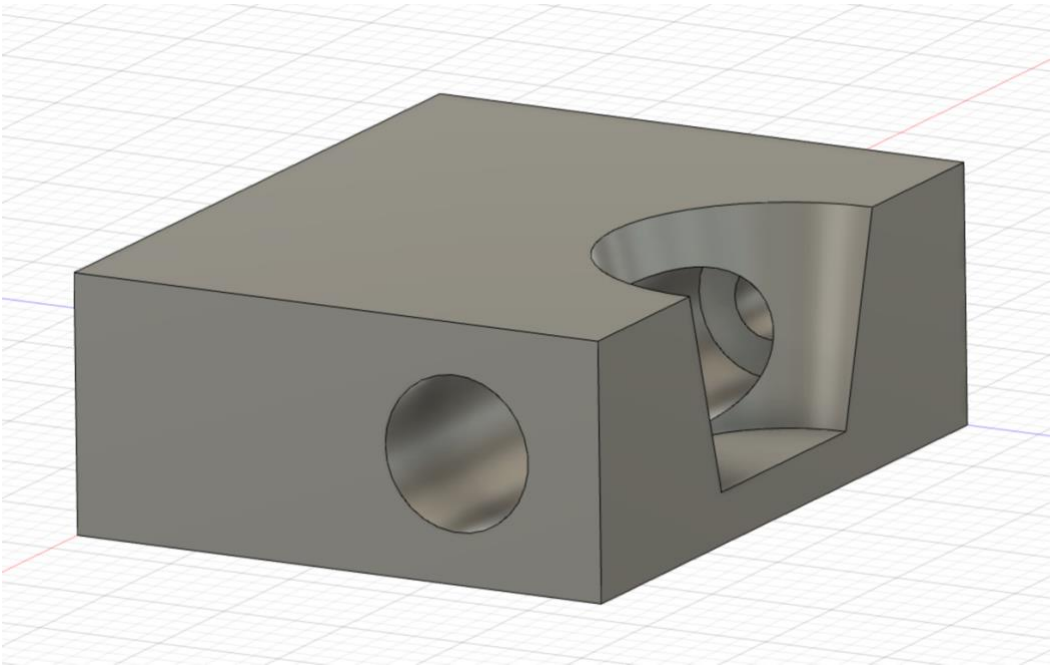
Robot Gripper

Two sets of grippers were designed and 3D-Printed to be able to grab all of the components involved. The glass tube was designed to be a standalone grip while the second grip handles both the plug and the mandrel. The tube grip is spaced with a gap between the mounting holes and the location to grab the tube to allow for the mandrel and plug grip to be able to move the plug and mandrel without causing interference when grabbing any part.



One side of Tube Grip

The mandrel and plug grip is a box shape with a conical gap left in the central area for the plug to fit into. The grip also features a channel for the mounting screws or nut to be able to pass through to allow a secure fit. We used foam adhesive to fill in the central portion of the passage to give a secure fit while grabbing the tube. A small notch was drilled out of the grip for the mandrel to be securely held onto during both indexing and transport to the assembly station.



One Side of Mandrel and Plug Grip

Delivery Base

The delivery base is made similarly to the tube dispenser but lacks any moving parts. It is simply the collection area for the finished assemblies that forms a sort of ramp for the tubes to go down where they can be collected later. Foam tape lines the bottom to prevent any breakage of glass. The robot drops the tubes on the higher side of a ramp and the tube rolls down to come to rest on padded stoppers.

Maintenance

For 3-D printed parts, make sure no extra load is being applied besides the load that is being received by the work. If the part breaks, then send the files provided to 3D print a new part.

For the tube dispenser, make sure that you're regularly checking the space between the gates and the brackets placed on the opposite side of the pneumatics. After multiple cycles, if the brackets were not tightened well, the gate might become loose and come out from its positions creating tube jams.

For the plug dispenser, make sure that the feeding tube is always clean so that the plugs can be fed smoothly with no interference as it goes down. Make sure that the tapered opening is not touched externally since small movements might cause the material to deform creating more plug jams.

For the robot maintenance instructions follow the instructions provided by **MOTO**MAN **MH5.**

Future Improvements

One of the future improvements would be building a less flexible tube grip. This could be done simply by building the grip with more infill, or by adding more material to the space between the mounting hole and the area where the tube is gripped. The difficulty of that is still allowing the mounting location to be reached. If a screw slot were used, testing would need to be completed to guarantee the tube could be securely gripped without slippage.

A second improvement that would be very helpful would be the extensive use of sensors to detect whether or not the assembly objects are in their proper positions before the robot moved to grab those items. An inductive sensor could be placed on the turret to ensure that the slots where the mandrel is are properly aligned to where the robot thinks it should be. A second sensor should be placed close to the turret to send feedback on whether or not there is a mandrel ready to be assembled. A sensor should also be placed at the end of the tube dispenser so the robot would not just grab air but would make sure a tube was in place to grab. A sensor would also be wise at the plug station to avoid any plug getting stuck and not coming out causing a catastrophic assembly failure and a mess of mandrels and broken tubes on the assembly table. With no plugs, nothing will stand on the assembly base. With no mandrel, there would be no grafts in each test tube. With no tubes, the assembled item would not be delivered to the end of the line. This would cause more plugs to be dropped onto the plug and mandrel already on the assembly station and be destroyed while also creating no end products until the situation was rectified. The last sensor could be placed on the tube dispenser to send feedback to the robot on whether a tube has been completely dispensed. This would stop any interference between the gate and the tubes and would prevent any future assembly failures when the robot goes to pick up the tube.

The third improvement to this design that would be helpful in future setups, would be adding a vacuum underneath the assembly base. This would help keep the plug positioned in one place without it falling if anything bumps it while it's being assembled. The idea is to use a larger vacuum so that the plug is held in place well while the robot assembles the rest. This would also help the assembly run faster because there would be no worry about fast movements tipping over the plug or assembly. This would overall improve our repeatability and success rate.

Performance Data

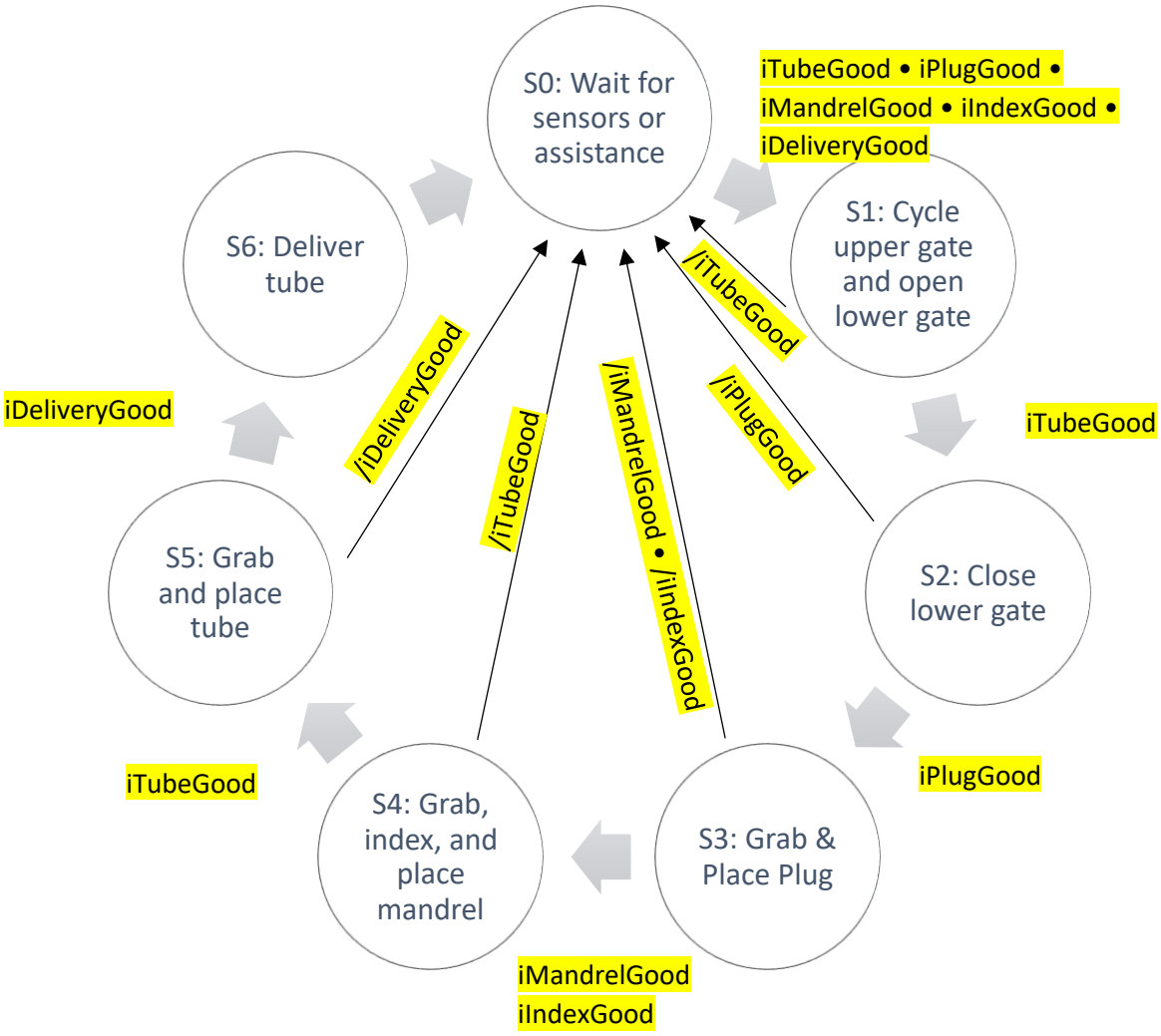
While not perfect, the culture tube assembly process proved to be moderately accurate and repeatable. Out of a sample size of 10, 80% of the trials were completely successful. Referencing the Stage Diagram below for individual steps, the culture tube loading mechanism operated with a 100% success rate (0-4). The plug dispenser, gripper, and placement movements were 80% successful (5-6). The mandrel grabbing and rotation of the turret had a 100% success rate (7-9). The insertion of the mandrel into the plug was 90% successful (10). Lastly, the grabbing, plug insertion, and placement of the assembled culture tube had an 80% success rate (11-14).

To bring the performance of our assembly process closer to production levels, several sensors would need to be added to stop production in the event of a failure. These sensors are highlighted

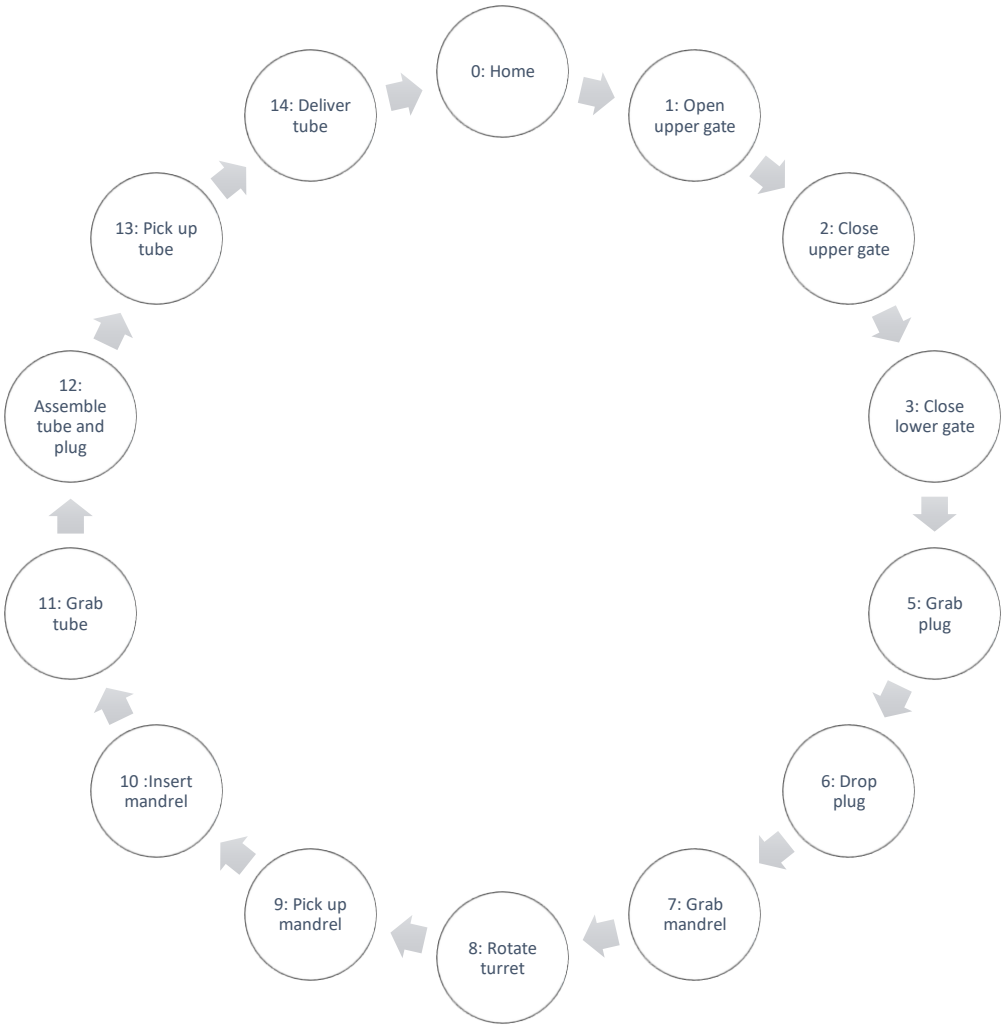
in the Stage Diagram below. Additionally, the plug dispenser, plug base, and mandrel gripper would need to be redesigned to reduce the chances of components bending or breaking due to cyclical fatigue.

Other Diagrams and Miscellaneous Photos

State Diagram (additional sensors are highlighted)

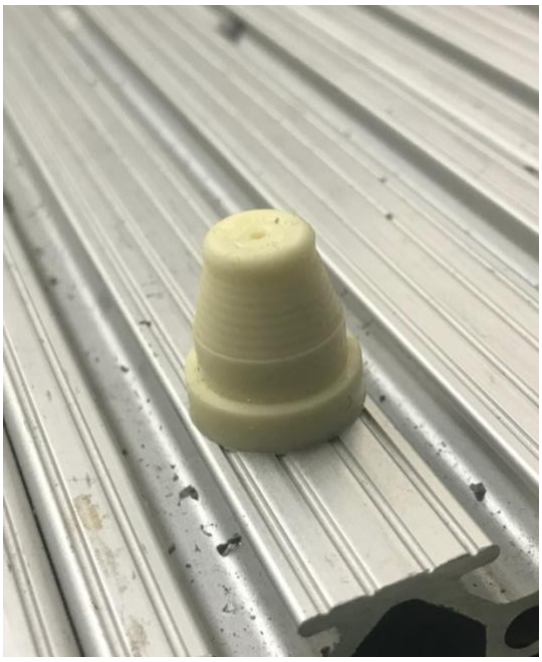


Movement Diagram



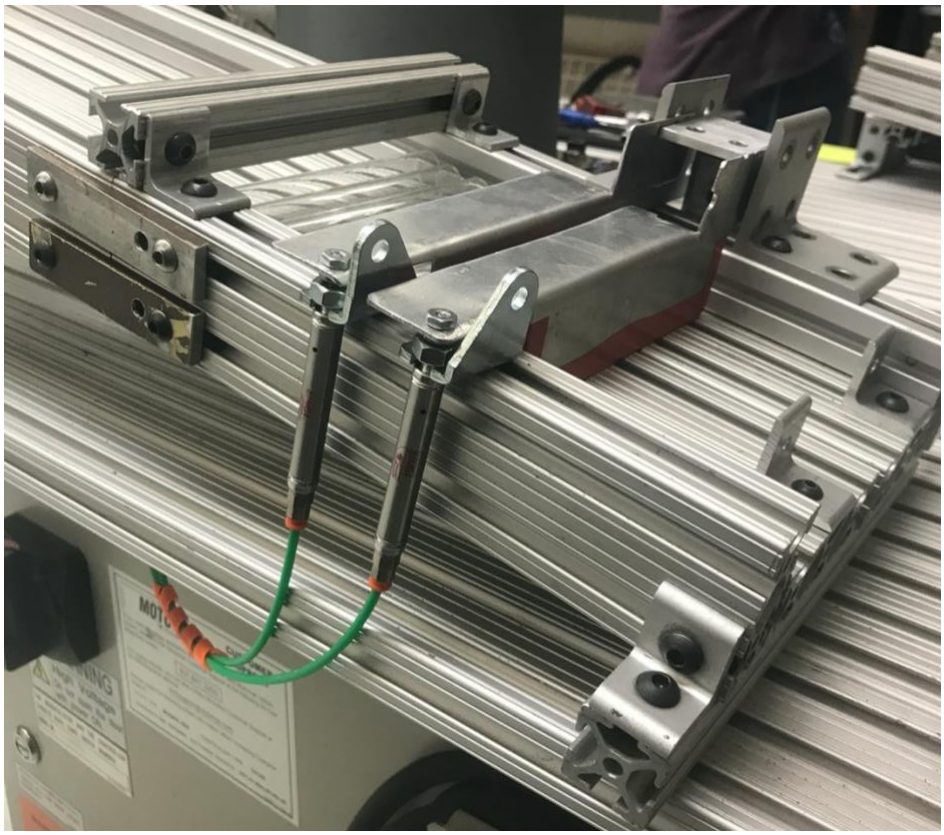
Pneumatic Valves Setup & Shortcuts

Component	Shortcut (Interlock + # below)	Pneumatic Channel (for code)
Grippers	4	12
Upper gate	6	14
Lower gate	1	9

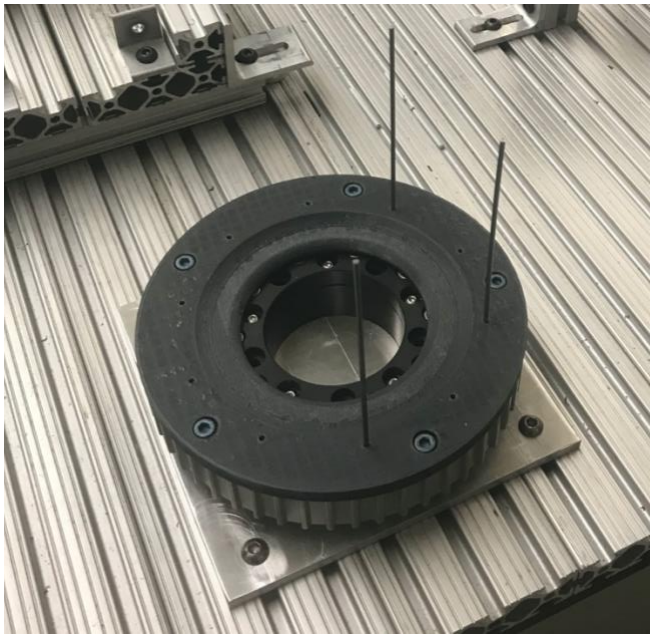


Final Plug Design

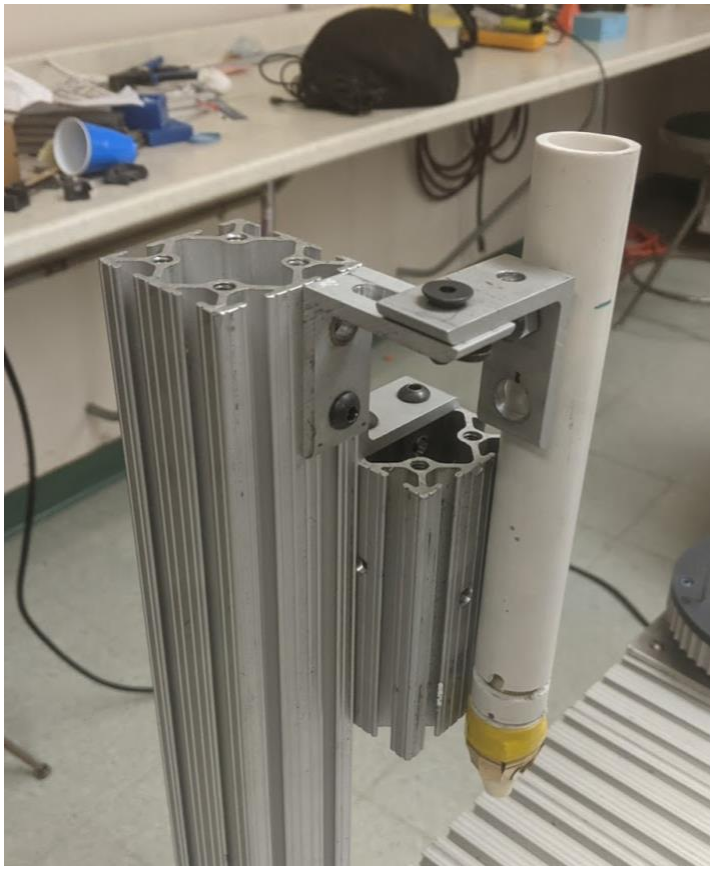
Assembly Station



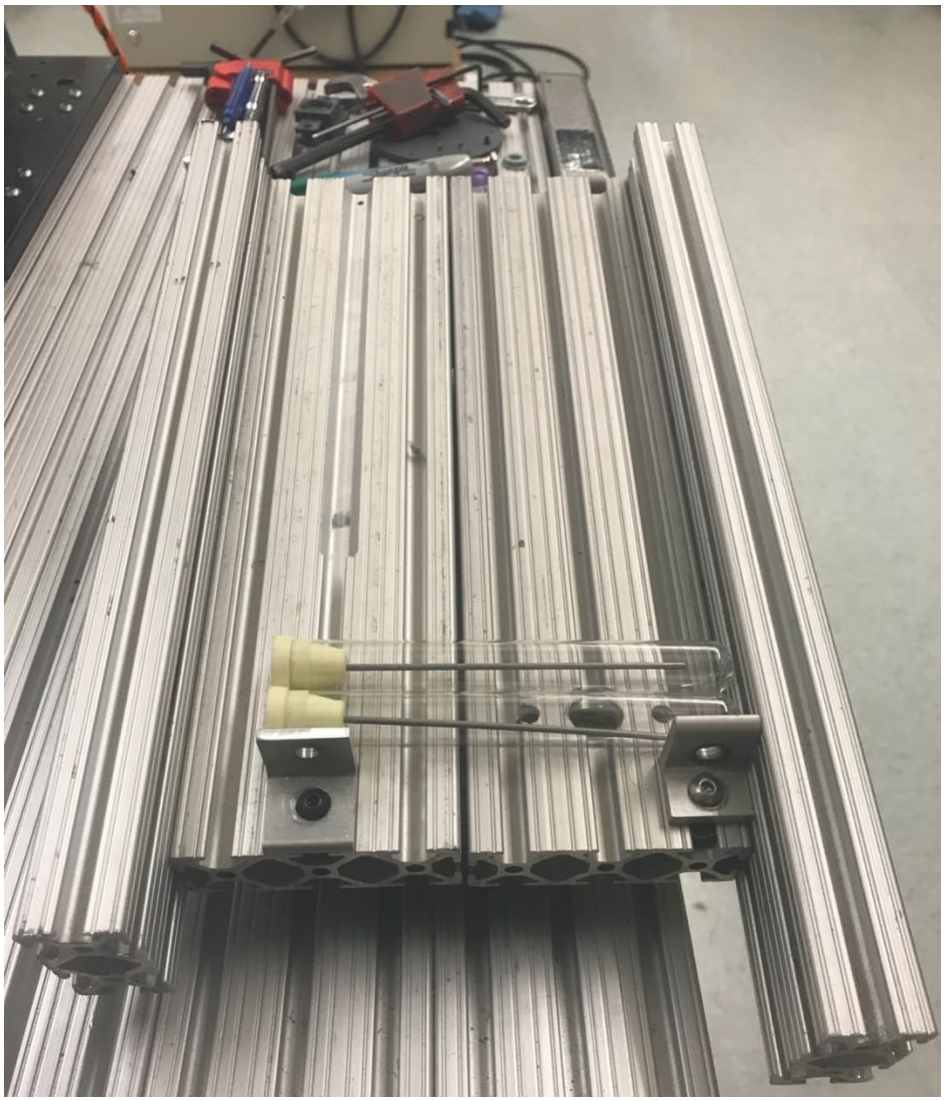
Tube Delivery w/ Pneumatically Actuated Arms



Mandrel Turret



Plug Dispenser



Delivery Station

Appendix

MOTOMAN Job Program

/JOB

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//POS

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///TOOL 0

///POSTYPE PULSE

///PULSE

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///POSTYPE ROBOT

///RECTAN

///RCONF 0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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///RCONF 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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P00004=374.223,13.628,-37.706,149.7836,-86.2880,29.4692

P00005=652.470,-249.099,-77.301,149.7817,-86.2887,29.4741

P00006=720.061,-163.092,-230.110,149.8451,-86.2886,-57.0760

///RCONF 1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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P00008=682.080,-237.478,-250.690,-64.3534,-89.5837,161.7455

P00009=718.611,-252.853,-250.690,-64.0201,-89.5828,161.4121

///RCONF 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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P00011=580.943,-311.188,129.718,149.8881,-86.2816,29.3621

///RCONF 1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

P00012=451.828,-340.723,87.776,-167.9819,-2.0593,88.8708

P00014=441.035,-346.226,-179.018,-169.5245,0.5157,91.5564

P00015=441.022,-346.225,98.633,-169.5224,0.5139,91.5585

P00017=437.875,109.367,93.033,-22.9581,88.4488,-112.4092

P00018=435.774,108.130,-26.513,-42.8453,88.0573,-132.2864

P00020=437.896,109.021,-134.971,-42.7806,88.0599,-132.2223

P00021=437.890,109.020,-139.057,-42.8544,88.0611,-132.2986

P00022=437.888,109.019,11.179,-42.8426,88.0614,-132.2874

///POSTYPE PULSE

///PULSE

P00023=20965,18134,-50837,504,-34214,-59579

P00024=89202,46873,-49833,5197,-17562,116175

P00025=89202,50463,-49582,5836,-15588,115752

///POSTYPE ROBOT

///RECTAN

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P00031=364.395,62.212,-14.310,29.3100,-87.7599,120.2733

///RCONF 1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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P00033=374.242,53.813,-162.000,29.4791,-87.7662,120.1018

///RCONF 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0

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///POSTYPE PULSE

///PULSE

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///POSTYPE ROBOT

///RECTAN

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P00105=375.522,15.629,-163.119,105.0983,-88.5392,74.0773

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///GROUP1 RB1
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DOUT OT#(14) OFF
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DOUT OT#(9) ON
WAIT IN#(10)=ON T=1.00
DOUT OT#(9) OFF
MOVL P000 V=100.0
MOVL P102 V=100.0
DOUT OT#(12) ON
WAIT IN#(10)=ON T=1.00
MOVL P103 V=15.0
DOUT OT#(12) OFF
WAIT IN#(10)=ON T=1.00
MOVL P099 V=100.0
MOVL P000 V=50.0
MOVL P003 V=100.0
MOVL P004 V=100.0
MOVL P105 V=50.0
MOVL P104 V=10.0
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DOUT OT#(12) ON
WAIT IN#(10)=ON T=0.50
MOVL P105 V=10.0
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MOVL P006 V=100.0
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MOVC P009 V=50.0
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DOUT OT#(12) OFF
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MOVC P008 V=10.0
MOVC P007 V=10.0
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MOVL P030 V=100.0
MOVL P031 V=100.0
MOVL P032 V=100.0
MOVL P033 V=5.0
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DOUT OT#(12) ON
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MOVL P031 V=100.0
DOUT OT#(12) OFF
MOVL P011 V=100.0
MOVL P012 V=50.0
DOUT OT#(12) ON
MOVL P014 V=100.0
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DOUT OT#(12) OFF
WAIT IN#(10)=ON T=1.00
MOVL P015 V=100.0
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MOVL P018 V=25.0
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MOVL P020 V=25.0
WAIT IN#(10)=ON T=0.50
MOVL P021 V=15.0
WAIT IN#(10)=ON T=1.00
MOVL P022 V=50.0
MOVL P023 V=100.0
MOVL P024 V=100.0
WAIT IN#(10)=ON T=0.50
MOVL P025 V=15.0
WAIT IN#(10)=ON T=0.50
DOUT OT#(12) ON
WAIT IN#(10)=ON T=1.50
DOUT OT#(12) OFF
MOVL P024 V=100.0
MOVJ P100 VJ=100.00
MOVL C00000 V=100.0
END
```