Axle Assembly Poke-Yoke

Chris Huesman
Indiana University - Purdue University Fort Wayne

Marc Reust
Indiana University - Purdue University Fort Wayne

Follow this and additional works at: http://opus.ipfw.edu/etcs_seniorproj_mcetid

Part of the Mechanical Engineering Commons

Opus Citation
MET 494
Final Report
4-27-15

Axle Assembly Poke-Yoke

Chris Huesman
Marc Reust
Introduction

Our team was contracted to design and fabricate an automated Poka-Yoke (mistake proofing) system to be retrofitted to an existing axle assembly and tack weld fixture in a local manufacturing facility. The problem was presented to us after this company’s management realized how easily these assemblies could be welded incorrectly, and that $20,000.00 worth of scrap could potentially be generated in one day.

The Problem

In the existing process there are 3 different assemblies that utilize the current fixture. Each assembly consists of a machined carrier casting with one of three different axle tubes pressed in and welded in place (this is done in a previous operation) and one of six different brackets slip fit over the axle tube and welded in place.

The slip fit diameter on the axle tubes are all the same dimension therefore an operator could potentially weld the wrong bracket onto the assembly. In the current process, two supervisors are required to visually confirm that the correct parts are present before the operator welds the brackets in place. This is a time consuming procedure which could easily be compromised if the operator became impatient while waiting for the supervisor to come around. This process still allows for the possibility of human error if the supervisor misses an incorrect assembly as well.

The Solution

In order to eliminate the possibility of an assembly error we designed a solution that addresses the following objectives:

1. Must not add additional time to the existing process.
2. Must be easy to use and train someone to use.
3. Must utilize the current fixture.
4. Must provide clear visual confirmation of test results.
5. Must not exceed a budget of $3000.00.

To accomplish this we used a combination of pneumatic cylinders, laser sensors, and proximity sensors interfaced with a PLC (programmable logic controller) to identify which parts are present.
The Build

In modern custom machine building, there is a close synergy between the designing side and the machining side that goes into a custom machine. These two aspects are important because when used appropriately together they can reduce manufacturing time and cost, prevent potential interferences or problems, and overall improve the quality of machine produced.

Design

For the design aspect of this project, Solid Works was used. This program allowed us to digitize all of the parts used in the axle assemblies, the purchased components and parts we had to build for the testing process.

With these parts digitized and in a 3D environment, we were able to position the work parts onto the fixture. From there we would build and create parts that would allow us to perform the test we would need. Whether it was putting a simple block in to raise a cylinder up an inch or a contoured piece that held a sensor on the swing arm, all were done in this environment first.

We were able to manipulate the pieces, add and remove material were need be, adjust hole spacing, change a design to eliminate a machining process, and swap out parts all at a click of a button. It is this ease of design and corrective measures that help maximize the efficiency of a project.

Once the parts were verified to not interfere and all necessary tests could be performed, 2D drawings (Appendix A) were created for each custom part that would have to be created. However these 2D prints were for reference only. The digital file of the 2D print is what was used to program the CNC machine g-code.

Machining

The 2D print file described above was imported into MasterCam. This program that can take these files and use them to produce g-code programs for CNC machines. This program reduces the input of programming to clicks instead of manually computing g-codes and typing them by hand into the control, once again, another step of efficiency.

In the program you will select geometry on the prints and then assign a tool path to it. This can be a simple point to drill a hole at or a contoured face to run an end mill along. Once assigned, these tool paths can be set to run at certain speeds, feeds, depths, climb milling or conventional milling. Once the tool paths are ready, the program will post the g codes for the selected operations and download them into the CNC machine.

Once downloaded, the machine can be cycled and perform the operations programmed.
Machining (Cont.)

The following list is how the various parts of this test station were created and the finish process they were given.

<table>
<thead>
<tr>
<th>Part</th>
<th>Manufacturing Process</th>
<th>Finish</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotary Riser (SD-2005)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Swing Arms (SD-2001)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Web Sensor Holder (SD-2002)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Cylinder Brackets (SD-2013, SD-2006)</td>
<td>Plasma Cut / Bend Press</td>
<td>Black Oxide</td>
</tr>
<tr>
<td>Laser Riser Base (SD-2010)</td>
<td>Vertical Machine Center</td>
<td>Black Oxide</td>
</tr>
<tr>
<td>Laser Mount (SD-2011)</td>
<td>Vertical Machine Center</td>
<td>Black Oxide</td>
</tr>
<tr>
<td>Tube Plug (SD-2009)</td>
<td>Manual Lathe</td>
<td>Black Oxide</td>
</tr>
<tr>
<td>Tube End (SD-2016)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Button Mount Riser (SD-2017)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Button Plate (SD-2018)</td>
<td>Vertical Machine Center</td>
<td>Black Anodizing</td>
</tr>
<tr>
<td>Light Tube (SD-2015)</td>
<td>Purchased</td>
<td>Glass Bead Blast</td>
</tr>
<tr>
<td>Laser Guard (SD-2019)</td>
<td>Plasma Cut / Bend Press</td>
<td>Black Oxide</td>
</tr>
</tbody>
</table>

Finishing

The parts were finished with either black oxide or black anodizing for two reasons. The first is for an extra layer of protection and the second is aesthetics. The steel parts received the black oxide finish. This finish is essential a controlled rust finish. The process converts the outer most surface of the parts to this rust and is black in color. The aluminum parts received the black anodizing. The second reason is for aesthetics. The parts have a cleaner and a more appealing look instead of shiny machined surfaces.

The light tube was clear polycarbonate that has been bead blasted. The blasting was done to put a satin finish on the tube. This roughed surface dulls the intensity of the LED lights. It also captures the light and produces a better indicator light.
**Programming**

Nearly, if not all automated machines today use an industrial computer, more specifically a PLC. These devices allow for a less complicated, smaller and more efficient control to be built for these machines. The PLC is the heart of the system controlling when to actuate solenoids or contacts, while also reading in inputs and other status.

For this project a Click PLC was used. This is an entry level, cost effective plc that suits the cost and performance aspect of this project. One of the nice things this plc has to offer is the free programming software, as compared to other higher end plc manufactures, were the programming software has to be purchased. The software was easily downloaded and installed from Automation Direct.

The main principle behind the programming was to divide it into easy to understand and corresponding sections. This was done thru the use of a main program and over four sub routines. This structure breaks down what would be a larger single program into smaller easy to troubleshoot sections.

Located in appendix D is the plc ladder diagram. The program will start in the main program then go into the tube length check sub routine. After a tube length has been determined it will jump back into the main program and then jump back into other sub routines until the check either passes or fails. This is shown by figure 2.

What is also nice about PLC’s is, if one were to go online with the plc while it is doing a check process, the status of inputs and ladder logic can be monitored. This allows for easy troubleshooting and diagnosis of problems if and when they were to occur.

*Figure 2: Program Logic Diagram*
**Electrical**

The electrical system of any machine is critical to its operation. It is in this system that the machine is able to provide power to components and communicate with sensors or devices. If it were to be wired wrong a component could not work or worse, become damaged. That is why it is important to correctly wire the machine.

**Wiring**

Wiring a machine is usually done by following a set of electrical prints (Appendix B). These prints show how the machine is wired between its main power coming in and the electrical components on it. The prints can also help in troubleshooting any possible electrical problem.

We used AutoCAD to produce our electrical prints. Using a generic electrical schematic layout, we created our prints for us to follow after we had specified all of the electrical components that will be used in the control panel and sensors on the test station.

**Panel Layout**

We used SolidWorks to digitally layout the control panel before we built it. This is an important step to ensure that there will be plenty of space in the panel. Always go with a slightly larger enclosure than what you need, if able to. This not only allows for extras features that may be added later but also space for possible forgotten/unforeseen needed components.

After a layout had been established, construction began. We used DIN mounted hardware which simplifies installation. DIN rail is a generic metal extrusion in which the electrical components can easily snap on to and be held in place. This eliminates the need to drill many mount holes and now can be done with just a few for each piece of rail.

**Enclosure**

The enclosure is the box where the panel and air solenoids are located. This box come pre assembled with the only required action to do are: mount the box, mount the panel inside, and put holes in it for the cables.

The holes for the cables where made by using a step drill and hydraulic knockout set. The step drill is preferred as it doesn’t catch as a normal drill would when going thru thinner sheet metals. Once the holes had been created we used a hydraulic knockout set to take them to their final size. The hydraulic knock out is essentially a large hole punch.

Once the holes were made, we installed cord grips to run our cables thru. The cord grips serve three purposes: seal the cabinet, protect the wires from strain, and protect the wires from a sharp edge if not used.
The Test Results

The test station performed very well throughout the testing. Although several program changes had to be made during this time to fix the pass/fail indicator not changing states, the test station performed 100 percent. It didn’t allow a bad part to pass and a good to fail. This is shown in the appendix E.

The Conclusion

Given the problem, the parameters, and the budget for this project, it was a success. The test station performs ideal and is a vast improvement on the original station. However, no project is complete without a bit of setbacks. These were minimal for us though. For example: a broken sensor, figuring out how to fix the program when a bug appeared, and some time restrictions due to work.

This project also came in under budget. As shown in appendix F, we came roughly 17 percent under budget. Granted if the machining was to be shopped out this would not have been the case.
Appendix

A. Part Prints Pg: 9 - 16
B. Electrical Prints Pg: 17 - 23
C. Pneumatic Print Pg: 24
D. PLC Ladder Logic Pg: 25 - 34
E. Test Results Pg: 35
F. Budget Pg: 36
G. Project Gantt Chart Pg: 37
H. Calculation Pg: 38
I. Assembly Drawing Pg: 39
J. Finished Photos Pg: 40
K. Bibliography Pg: 41
Appendix A: Part Prints
Appendix B: Electrical Prints
Chuesman / Reust

Diagram showing electrical connections with labels and symbols. Details include connections to PLC and supply sources.

Sheet: PDQ

AXLE POKA-YOKE
24 VDC ELEMENTARY

Scale: 1/2 in = 1 ft
Appendix C: Pneumatic Print
Appendix D: PLC Ladder Logic

Actuation Of Cycle Start Push Button Starts Tube Length Check Sub-Program.

Cycle_Start_PB
- X005
- Call Tube_Length_Check

42121-31380-71-C Tube was detected, calls 42101-U3700-71-C Assembly Check Sub. Prog.
42121_31380_71_C_Tube
- C1
- Call 42101-U3700-71-C Assem.

42121-36820-71 Tube was detected, calls 42101-U3760-71-C Assembly Check Sub. Prog.
42121_36820_71_Tube
- C2
- Call 42101-U3760-71-C Assem.

42121-31391-71-A Tube was detected, calls 42101-U3780-71-C Assembly Check Sub. Prog.
42121_31391_71_A_Tube
- C3
- Call 42101-U3780-71-C Assem.


- Pass_Bit
- C4
- Call Pass_Loogic

Actuation Of The Reset Push Button Starts Reset Logic Sub-Program.

Reset_PB
- X005
- Call Reset_Loogic

(END)
Resets Coils for Straight Cylinders Home Position.
Sol_4_Cyls_Home_Pos
  ■ V004
        (RST)

Sets Coils For Straight Cylinders Test Position.
Sol_2_Cyls_Test_Pos
  ■ V002
        (SET)

If Both Lower Pins and Upper Cylinder Switches are made and The Lower Cylinder Switches are Not Made, The Part Passes.

42101_U3730_T1_C
  ■ C4
        (SET)
Reset of straight cylinders home position solenoid

Sol_4_Cylts_Home_Pos

Set of straight cylinders test position solenoid

Sol_2_Cylts_Test_Pos

Lower Pins, Upper Cylinder Switches, and Lower Cylinder Switches need to be made in order to pass part

Right_Lower_Pin Left_Lower_Pin Right_Lower_1нд Left_Lower_1нд Right_Upper_1нд Left_Upper_1нд

Pass Bit

Return,
Reset of rotary cylinders home position solenoid
   Sol_3_Rot_Cyl_home
   P003
   RST

Set of rotary cylinders set position solenoid
   Sol_1_Rot_Cyl_Set P
   P001
   SET

Both Upper Pins, Left and Right Web Detect Sensors Need to be Made in order to pass

Right_Upper_Pin
   X102
Left_Upper_Pin
   X104
Left_Web
   X106
Right_Web
   X105
   Pass Bit
   C4
   SET

42101-U3780-71-C
   Bit
   C9
   SET

Return
Subroutine Program: Pass Logic (Page 2 of 2)

If either Assembly bits that require the lower pins are on, those pins have to be removed in order to reset the program, green light, pass bit, and assembly bits.

- 42101_U0780_71_D_Bit
  - C0
- 42101_U0780_71_D_Bit
  - C7
- Right_Lower_Pin
  - X101
- Left_Lower_Pin
  - X103
- Green_Light_Relay
  - Y005

If Assembly bit that require the upper pins are on, those pins have to be removed in order to reset the program, green light, pass bit, and assembly bit.

- 42101_U0780_71_D_Bit
  - C0
- 42101_U0780_71_D_Bit
  - C7
- Left_Upper_Pin
  - X104
- Right_Upper_Pin
  - X102
- Green_Light_Relay
  - Y005

Return

Page 6 of 10 (Total Pages)
Reset of rotary test position solenoid
   Sol_1_Rot_Cyl_Test_LP
   001
      RST

Reset of straight test position solenoid
   Sol_2_Cyl_Test_Pos
   002
      RST

Reset of tube call out bits, Pass Bit
   42121_313
   50_31c_31_c
   use
   Pass_Bit
   01
   04
      RST
      C4

Set of rotary home position solenoid
   Sol_3_Rot_Cyl_Home_Pos
   003
      SET

Set of straight home position solenoid
   Sol_4_Cyls_Home_Pos
   004
      SET

Reset of green light
   Green_Light_Relay
   005
      RST

Return
### Appendix E: Test Results

#### WELD CELL POKE-YOKE FUNCTIONAL TEST

<table>
<thead>
<tr>
<th>ASSEMBLY VARIATION</th>
<th>EXPECTED RESULT</th>
<th>TEST ATTEMPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CARRIER TUBE PASS/FAIL 1 2 3 4 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42211-U3700-71</td>
<td>PASS</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42212-U3700-71</td>
<td>PASS</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42211-U3760-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42212-U3760-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42211-U3780-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42212-U3780-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42211-U3700-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>42212-U3700-71</td>
<td>FAIL</td>
<td>1 2 3 4 5</td>
</tr>
</tbody>
</table>

ASSEMBLY VARIATION: 42111-U3700-71

### Test Attempt Results

- **WELD CELL POKE-YOKE FUNCTIONAL TEST**
- **RIGHT BRACKET**
- **EXPECTED RESULT**: 42211-U3700-71 FAIL
- **TEST ATTEMPT**: 42212-U3700-71 FAIL
- **EXPECTED RESULT**: 42211-U3760-71 FAIL
- **TEST ATTEMPT**: 42212-U3760-71 FAIL
- **EXPECTED RESULT**: 42211-U3780-71 FAIL
- **TEST ATTEMPT**: 42212-U3780-71 FAIL
- **EXPECTED RESULT**: 42211-U3700-71 FAIL
- **TEST ATTEMPT**: 42212-U3700-71 FAIL

ASSEMBLY VARIATION: 42112-U3700-71

### Additional Test Results

- **EXPECTED RESULT**: 42212-U3700-71 FAIL
- **TEST ATTEMPT**: 42211-U3780-71 FAIL
- **EXPECTED RESULT**: 42211-U3760-71 FAIL
- **TEST ATTEMPT**: 42212-U3760-71 FAIL
- **EXPECTED RESULT**: 42212-U3780-71 FAIL
- **TEST ATTEMPT**: 42211-U3780-71 FAIL
Appendix F: Budget

<table>
<thead>
<tr>
<th>VENDOR</th>
<th>DESCRIPTION</th>
<th>PART #</th>
<th>PRICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANALOG INPUT MODULE</td>
<td>C0-04AD-1</td>
<td>$ 89.00</td>
<td></td>
</tr>
<tr>
<td>SINK/SOURCE INPUT MODULE</td>
<td>C0-08ND3</td>
<td>$ 33.00</td>
<td></td>
</tr>
<tr>
<td>PRESSURE GAUGE</td>
<td>PGU14</td>
<td>$ 17.75</td>
<td></td>
</tr>
<tr>
<td>PRESSURE REGULATOR</td>
<td>PRU14</td>
<td>$ 20.25</td>
<td></td>
</tr>
<tr>
<td>Y REDUCER 1/4-1/8 (PKG OF 5)</td>
<td>URY-14-18</td>
<td>$ 18.50</td>
<td></td>
</tr>
<tr>
<td>5 PORT 2 POSITION SOLENOID VALVE</td>
<td>AVS-5323-24D</td>
<td>$ 81.00</td>
<td></td>
</tr>
<tr>
<td>2 STATION AIR MANIFOLD</td>
<td>AM-532</td>
<td>$ 9.75</td>
<td></td>
</tr>
<tr>
<td>SOLENOID CABLE</td>
<td>SC9-LS24-3</td>
<td>$ 44.00</td>
<td></td>
</tr>
<tr>
<td>9/16in BORE 3in STROKE AIR CYLINDER</td>
<td>A09030DD-M</td>
<td>$ 118.00</td>
<td></td>
</tr>
<tr>
<td>MAG POSITION SWITCH PNP N.O</td>
<td>CPS-AP-F</td>
<td>$ 80.00</td>
<td></td>
</tr>
<tr>
<td>MAG POS SWITCH CABLE</td>
<td>CDD8-0A-020-A1</td>
<td>$ 33.00</td>
<td></td>
</tr>
<tr>
<td>SWITCH BAND</td>
<td>CPSSB-14</td>
<td>$ 11.00</td>
<td></td>
</tr>
<tr>
<td>FLOW CONTROL METER OUT (PKG OF 2)</td>
<td>FVS14-18N</td>
<td>$ 25.00</td>
<td></td>
</tr>
<tr>
<td>FLOW CONTROL METER OUT (PKG OF 2)</td>
<td>FVS18-10N</td>
<td>$ 21.00</td>
<td></td>
</tr>
<tr>
<td>MALE ELBOW FOR CYLINDERS (PKG OF 5)</td>
<td>ME18-10N</td>
<td>$ 11.00</td>
<td></td>
</tr>
<tr>
<td>1/8in TUBING (100FT) BLU</td>
<td>PU18BLU100</td>
<td>$ 13.50</td>
<td></td>
</tr>
<tr>
<td>1/8in TUBING (100FT) BLK</td>
<td>PU18BLK101</td>
<td>$ 13.50</td>
<td></td>
</tr>
<tr>
<td>1/4in TUBING (100FT) BLU</td>
<td>PU14BLU100</td>
<td>$ 19.00</td>
<td></td>
</tr>
<tr>
<td>1/4in TUBING (100FT) BLK</td>
<td>PU14BLK101</td>
<td>$ 19.00</td>
<td></td>
</tr>
<tr>
<td>3/8 MNPT-1/4 TUBE ELBOW (PKG OF 5)</td>
<td>ME14-38N</td>
<td>$ 7.75</td>
<td></td>
</tr>
<tr>
<td>3/8 MNPT-1/4 TUBE STRAIGHT (PKG OF 5)</td>
<td>MS14-38N</td>
<td>$ 6.00</td>
<td></td>
</tr>
<tr>
<td>1/4 FEMALE BULKHEAD (PKG OF 5)</td>
<td>FB14-14N</td>
<td>$ 15.00</td>
<td></td>
</tr>
<tr>
<td>1/4 TUBE BULKHEAD (PKG OF 5)</td>
<td>U14</td>
<td>$ 13.00</td>
<td></td>
</tr>
<tr>
<td>1/4 T UNION (PKG OF 5)</td>
<td>UT14</td>
<td>$ 8.25</td>
<td></td>
</tr>
<tr>
<td>1/4 ELBOW (PKG OF 5)</td>
<td>UL14</td>
<td>$ 11.50</td>
<td></td>
</tr>
<tr>
<td>1/8 ELBOW (PKG OF 5)</td>
<td>UL18</td>
<td>$ 14.00</td>
<td></td>
</tr>
<tr>
<td>1/4 SILENCER (PKG OF 2)</td>
<td>SBC</td>
<td>$ 3.00</td>
<td></td>
</tr>
<tr>
<td>ENCLOSURE</td>
<td>N1C1216065</td>
<td>$ 84.00</td>
<td></td>
</tr>
<tr>
<td>PROX CABLE</td>
<td>CDD8-0A-020-A1</td>
<td>$ 33.00</td>
<td></td>
</tr>
<tr>
<td>10A RELAY</td>
<td>QL2N1-D24</td>
<td>$ 9.75</td>
<td></td>
</tr>
<tr>
<td>RELAY SOCKET</td>
<td>SLO80D</td>
<td>$ 4.00</td>
<td></td>
</tr>
<tr>
<td>24V POWER SUPPLY 3.75A 90W</td>
<td>PSC-24-090</td>
<td>$ 87.00</td>
<td></td>
</tr>
<tr>
<td>12V POWER SUPPLY 2.5A 30W</td>
<td>PSC-12-030</td>
<td>$ 57.00</td>
<td></td>
</tr>
<tr>
<td>POLYCARBONATE TUBE</td>
<td>3161T31</td>
<td>$ 17.88</td>
<td></td>
</tr>
<tr>
<td>PIPE PLUG</td>
<td>4452KS43</td>
<td>$ 6.81</td>
<td></td>
</tr>
<tr>
<td>CORD GRIPS</td>
<td>7807K94</td>
<td>$ 8.46</td>
<td></td>
</tr>
<tr>
<td>55MM ORING</td>
<td>9262K407</td>
<td>$ 5.45</td>
<td></td>
</tr>
<tr>
<td>51MM ORING</td>
<td>9262K751</td>
<td>$ 6.32</td>
<td></td>
</tr>
<tr>
<td>TERMINAL JUMPERS</td>
<td>11354412</td>
<td>$ 26.00</td>
<td></td>
</tr>
<tr>
<td>SINGLE LEVEL TERMINAL BLOCKS</td>
<td>11548603</td>
<td>$ 51.76</td>
<td></td>
</tr>
<tr>
<td>SENSOR TERMINAL CONNECTORS</td>
<td>11554212</td>
<td>$ 52.06</td>
<td></td>
</tr>
<tr>
<td>SICK 8MM PROX</td>
<td>1040838</td>
<td>$ 76.80</td>
<td></td>
</tr>
<tr>
<td>SICK DT35 LASER DISTANCE MEASURING</td>
<td>1057652</td>
<td>$ 588.37</td>
<td></td>
</tr>
<tr>
<td>FABCO ROTARY ACUATOR</td>
<td>FRC20X180</td>
<td>$ 525.76</td>
<td></td>
</tr>
</tbody>
</table>

**Total Budget** $3,000.00  
**Cost** $2,491.17  
**Remainder** $508.83  
**% Underbudget** 16.96%
## Appendix G: Project Gantt Chart

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Start</th>
<th>Finish</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Design (Planned)</td>
<td>1/27/2015</td>
<td>2/24/2015</td>
<td>4w 1d</td>
</tr>
<tr>
<td>2</td>
<td>Design (Actual)</td>
<td>1/27/2015</td>
<td>2/24/2015</td>
<td>4w 1d</td>
</tr>
<tr>
<td>3</td>
<td>Ordering of parts (Planned)</td>
<td>2/24/2015</td>
<td>3/16/2015</td>
<td>3w</td>
</tr>
<tr>
<td>4</td>
<td>Ordering of parts (Actual)</td>
<td>2/24/2015</td>
<td>3/10/2015</td>
<td>3w</td>
</tr>
<tr>
<td>5</td>
<td>Fabrication (Planned)</td>
<td>3/3/2015</td>
<td>3/31/2015</td>
<td>4w 1d</td>
</tr>
<tr>
<td>6</td>
<td>Fabrication (Actual)</td>
<td>3/10/2015</td>
<td>4/17/2015</td>
<td>5w 4d</td>
</tr>
<tr>
<td>7</td>
<td>Assembly (Planned)</td>
<td>3/17/2015</td>
<td>4/3/2015</td>
<td>2w 4d</td>
</tr>
<tr>
<td>8</td>
<td>Assembly (Actual)</td>
<td>3/17/2015</td>
<td>4/17/2015</td>
<td>4w 4d</td>
</tr>
<tr>
<td>9</td>
<td>Programming (Planned)</td>
<td>3/17/2015</td>
<td>4/3/2015</td>
<td>2w 4d</td>
</tr>
<tr>
<td>10</td>
<td>Programming (Actual)</td>
<td>3/24/2015</td>
<td>4/17/2015</td>
<td>3w 4d</td>
</tr>
<tr>
<td>12</td>
<td>Testing (Actual)</td>
<td>4/17/2015</td>
<td>4/30/2015</td>
<td>2w</td>
</tr>
</tbody>
</table>
Appendix H: Calculation

\[ I = \frac{763811253}{14} = 0.001124 \]

\[ \Delta_{\text{max}} = \frac{FL^3}{3EI} \]

\[ F = \frac{\Delta_{\text{max}}EI}{L^3} \]

\[ F_{\text{max}} = \frac{300 \times (30 \times 10^6) \times 100}{125} = 51.7461 \text{bf} \]

Detected from lightest component
\[ N = mg \]
\[ N = 47.61 \text{bf} \]

Max cylinder force with 1.5 safety factor
\[ F_{\text{max}} = \frac{F}{1.5} \]
\[ F_{\text{max}} = \frac{6.348}{1.5} = 6.3481 \text{bf} \]

\[ F = \mu N \]
\[ \mu = 0.2 \]
\[ F = 0.2(47.61) = 9.522 \text{bf} \]

Max air pressure determined from lowest max cylinder force.
\[ S_{\text{cylinder}} = \frac{\pi d^2}{4} \]
\[ S_{\text{cylinder}} = \frac{\pi (2.5)^2}{4} = 243505 \text{in}^2 \]

\[ P_{\text{max}} = \frac{F_{\text{max}}}{S_{\text{cylinder}}} \]
\[ P_{\text{max}} = \frac{6.348}{243505} = 25.5448 \text{psi} \]
Appendix I: Assembly
Appendix J: Finished Photos
Appendix K: Bibliography

Bibliography


