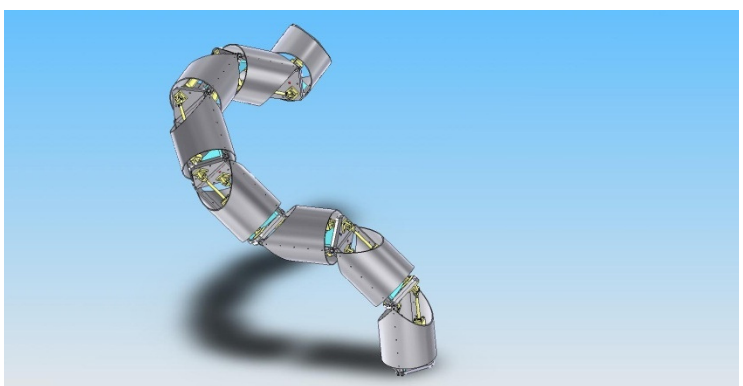
UNIVERSITY OF
Waterloo

Faculty of Engineering
Department of Mechanical & Mechatronics Engineering
ME482 Final Report

Hydrabot

The Modular Electro-Hydraulic Robot Arm



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Summary

Modular robot arms are kinematic chains consisting of, as the name implies, modular links. The modularity gives the user flexibility in the number of degrees of freedom in the robot arm, as well as the shape of the arm. Modular robot arms have applications wherever a high number of degrees of freedom are needed, such as when the arm is expected to manoeuvre in a confined space.

This report discusses the results of a prototype that uses hydraulic actuators in order to increase the payload and the maximum number of modules that can be supported in a modular robot arm. In this design, the modules are each powered by two hydraulic cylinders, which are controlled by a proportional directional valve. Each module adds one degree of freedom to the arm.

The goal of this project was to have a prototype consisting of two modules built, and a position control algorithm implemented, by the design symposium on March 23, 2009. Sure enough, the goals were met, and the robot arm made a very impressive exhibit at the symposium. It ran non-stop throughout the entire symposium, where it was programmed to complete a pre-determined sequence of closed-loop movements. In the symposium, the robot arm completed nearly 2,000 consecutive movements.

This report discusses the design changes from the design report, designs of some of the sub-systems that were not discussed in detail in the design report (such as the design of the controller and electronics), issues that arose during manufacturing, assembly, and testing, the testing protocols used and the test results, and discrepancies between the planned and actual budget and schedule. Finally, the report ends with conclusions and some recommendations regarding the design of the module.

Overall, the design is deemed to be successful as it met all of the requirements and constraints set forth at the beginning of the project, and relatively few issues arose during manufacturing, assembly, and testing.

I. Introduction

1.1 Project Background

Modular robot arms are kinematic chains consisting of identical, modular links capable of moving with respect to each other. Since the links are modular, the number of degrees of freedom in the arm is easily adjustable by simply adding or subtracting modules. Most modular robots are also reconfigurable, meaning that the user has flexibility in the orientation of the modules, and thus the shape of the robot arm.

Such robot arms have found applications wherever a robot arm with many degrees of freedom is needed, such as when the robot arm is expected to reach around an object or manoeuvre itself into a confined space such as a pipe, duct, or small compartment.

1.1.1 Needs Assessment

There is a limit to the number of modules in a robot arm, which is determined by the torque and weight of each module. Each module needs to have enough torque to support the modules above it. This problem is commonly solved by making the lower modules in the arm larger than the upper ones (since the lower modules need to support more weight than the upper modules). However, this means that the modules are not identical to each other, which takes away from the convenience of simply adding or subtracting a module from the robot arm. This project attempts to design a module with a high enough power-to-weight ratio, such that a modular robot arm can consist of many (i.e. up to 20) *identical* modules (identical meaning the lower modules are not larger than the upper ones).

1.1.2 Objectives

This project attempts to increase the number of allowable modules in a modular and reconfigurable robot arm by using hydraulic actuators, since hydraulic actuators have higher power-to-weight ratios than electrical actuators. It is expected that certain compromises will need to be made in order to do this, such as the cost and size of the modules. However, ultimately, this design should allow greater number of modules in the arm.

1.1.3 Goals

The goal of this project is to have a working proof-of-concept prototype built consisting of two modules by the design symposium on March 23, 2009. A simple control algorithm is also to be developed that will position the modules to some desired angles.

1.1.4 Requirements, Constraints, and Criteria

The robot arm needs to be safe to operate. Some safety concerns that must be addressed in the design of the robot arm are that:

- The user should be able to de-pressurize the oil in the system at will
- The robot should not collapse in case it is under load and a power failure occurs

Furthermore, re-configuring the robot arm (i.e. adding or subtracting a module, or changing the orientation of a module) should be easy. For example, it should not require the user to disconnect and reconnect hoses.

The following two constraints apply to this project:

- The cost of each module should not exceed $1500
- The maximum number of modules allowable in the robot arm should be greater than 5 (assuming the robot arm is planar), since this is the maximum number of modules in electrical modular robot arms

The following criteria are used to judge the design alternatives in this project:

- *Size* – Should be minimized since many applications for modular and reconfigurable robots require the arm to manoeuvre into tight spaces
- *Cost* – Should be minimized as is the case for all products
- *Power-to-weight ratio* – Should be maximized since this ratio is the main factor in the determination of the maximum number of modules in the robot arm

1.2 Outcomes

The robot arm was successfully completed in time to make an impressive exhibit at the design symposium on March 23rd, 2009 at the Student Life Centre at the University of Waterloo. The prototype met all of the requirements and constraints discussed in the previous section, with one exception: the payload of the prototype has not been tested. However, according to theoretical calculations, the robot arm should also meet the payload constraint.

This report discusses design changes from the design presented in the design report, any design which was not included in the design report (such as controller design and electronics design) [1], the fabrication and assembly of the prototype, discrepancies between the planned and actual schedule and budget, and operating procedures for safe operation of the robot arm. Finally, this report discusses some conclusions and recommendations.

II. Setup and Equipment

The setup used in the project is shown in Figure 1 below. As labelled in Figure 1, the setup consists of a computer (Pentium 4 CPU 3.07 GHz, 512 MB RAM) equipped with Labview 7.1 and a National Instruments PCI-6221 DAQ card to monitor the potentiometers and control the valves' solenoids, electronics to amplify the computer's signals in order to drive the solenoids, a hydraulic powerpack to supply pressurized oil, and the robot itself.

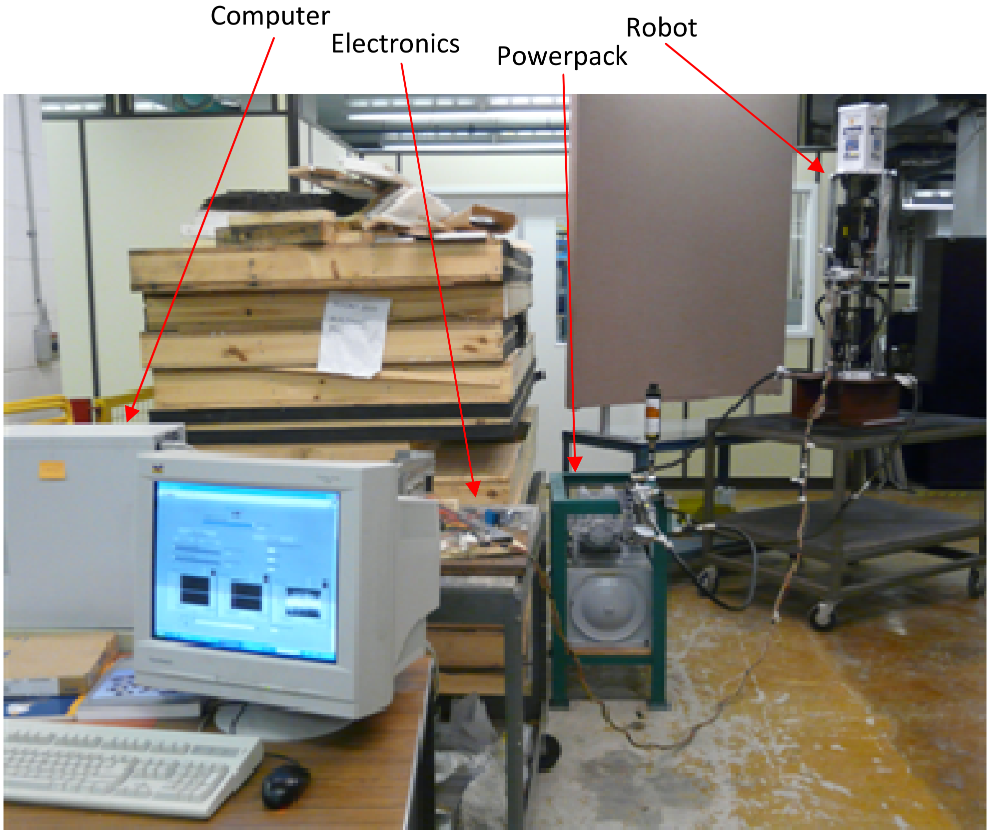


Figure 1 Project setup

The design of the control software and the electronics will be discussed later in this report. The powerpack consists of a 1 hp AC induction motor, a 2 cc fixed displacement gear pump, a pressure relief valve with adjustable setting, a return-line filter, a pressure filter which was donated by MP Filtri, a 1-quart accumulator (pre-charged to around 100 psi), and a tank with a volume of about 20 L. Assuming the motor rotates at 1725 rpm and there is zero leakage across the pump, the pump produces a flow of 3.45 lpm. However, the flow coming from the powerpack is greater than this since the accumulator is used to supplement the pump's flow.

III. Notable Design Changes

The following sub-sections discuss the main design changes made to the design presented in the design report. The as-built engineering drawings are provided in Appendix C.

3.1 Drillings added to reduce frictional losses

In the initial design, some of the channels joined in acute angles, which would result in excessive frictional losses. It was not possible to remove the acute junctions, but four more drillings were added to the manifold to provide an alternate flow path consisting only of perpendicular and obtuse junctions, which cause much less frictional losses. This change is illustrated in Figure 2 below.

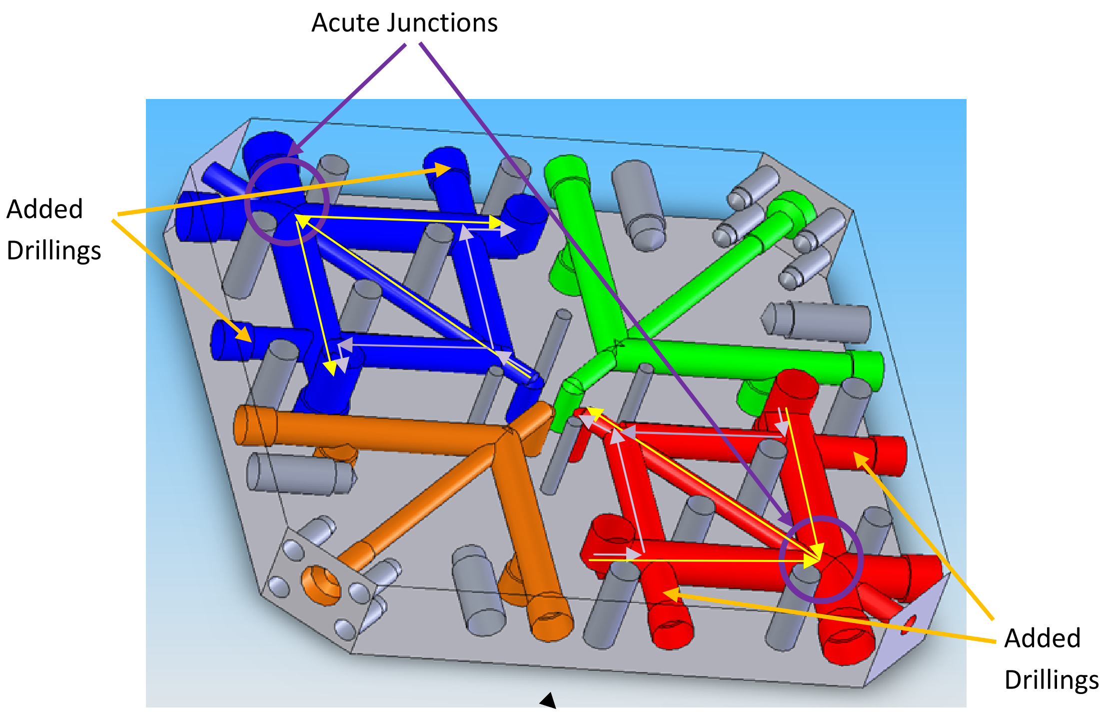


Figure 2 CAD model of manifold plate showing the flow path of the original design (in yellow arrows) and the alternate flow path (in gray arrows) with reduced frictional losses

3.2 Port Threads Changed from SAE to NPT

The initial design used SAE threads to attach the fittings, since SAE connections are much less prone to leaks than are NPT connections [2]. However, the threads needed to be changed to NPT since the University of Waterloo does not have SAE taps.

3.3 Hose Routing for Transmitting Oil between Modules

Each module has two hoses to transmit oil to the next module in the link (one for pressurized oil and the other for oil returning to the tank). The original design was to have these hoses run straight vertically (i.e. the pressure port of the top plate was directly above the pressure port of the base plate, and, similarly, the tank port of the top plate was directly above the tank port of the base plate). However, such a configuration subjects these two hoses to a great deal of stress as the top plate rotates from -45° to 45°. Therefore, the new design has the hoses routed diagonally to the opposite corner of the module (i.e. now the pressure port of the top plate is directly above the tank port of the base plate, and, similarly, the tank port of the top plate is directly above the pressure port of the base plate). This is illustrated in Figure 3 below. Since the bottom and top plates are symmetrical, this change did not affect the engineering drawings or the manufacturing of the plates. It only changed the coloring of the channels in the 3D model (as shown in the Figure 3 below).

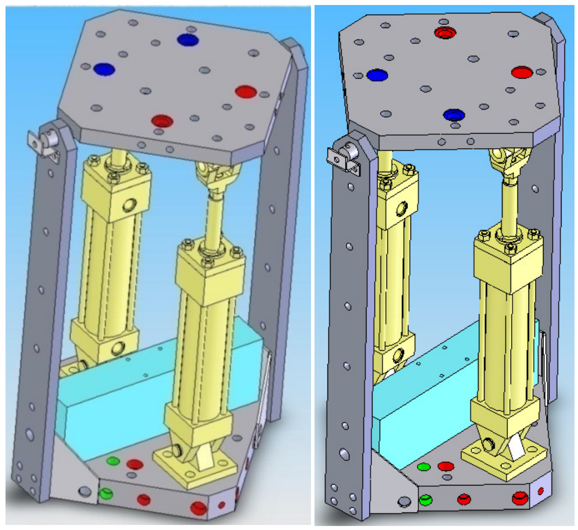


Figure 3 3D models of original (left) and new (right) design. Note that, in the original design, the pressure (red) port of the base plate is directly below the pressure port of the top plate, whereas, in the new design, the pressure port of the base plate is diagonal from the pressure port of the top plate (and similarly for the tank (blue) port).

3.4 Cylindrical Housing Excluded from Prototype

The cylindrical housing which encircled the module was not fabricated for the prototype, since it was too expensive to fabricate. Originally, the housing was going to be fabricated out of a pipe. However, a pipe that size (12.75" OD) turned out to be very expensive (~150/module), and thus it would be actually cheaper to have a technician from the Engineering Machine Shop fabricate the housing out of sheet aluminium (~$65/module). Although this housing was included to provide support against twisting and bending, it is not necessary for a prototype consisting of only two modules.

3.5 Final Design

Figure 4 below is a photograph of one of the modules after assembly:

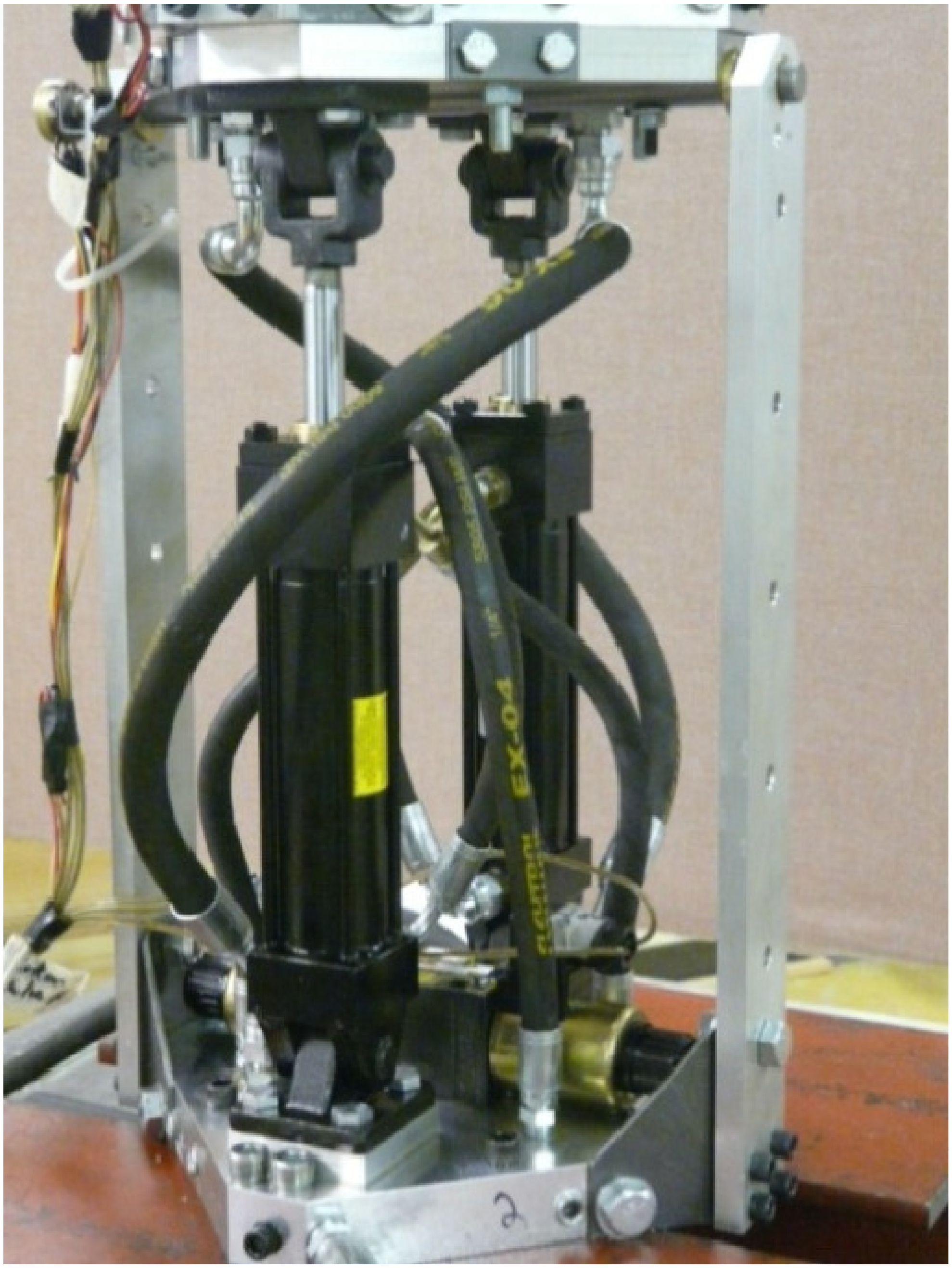


Figure 4 Photograph of one of the modules.

IV. Electronic Design

The electronics are used to amplify the computer's signals in order to drive the valves' solenoids. Each valve has two solenoids, and each solenoid is driven by its own power op-amp (i.e. there are two op-amps per valve). Since each valve should only have one of its solenoids energized at any given time (otherwise, the forces from the solenoids produce onto the valve's spool will cancel each other out), a switch is used to select the appropriate power op amp for each valve. For each valve, its analog command voltage is sent to the switch, and a digital logic pin on the switch decides which of the valves' solenoids gets energized.

The electrical schematic is shown in Appendix A.

V. Controller Design

Before designing the controller, it is first necessary to model the plant, which consists of the valve, cylinders, and the kinematic relationship between cylinder extension and top plate rotation. Feedback of the rotation of each module is obtained by rotary potentiometers, and the controller sends a command voltage to the valve according to the error between the actual rotation (as measured by the rotary potentiometers) and the desired rotation. Therefore, the closed-loop system can be modeled by the block diagram shown in Figure 5 below:

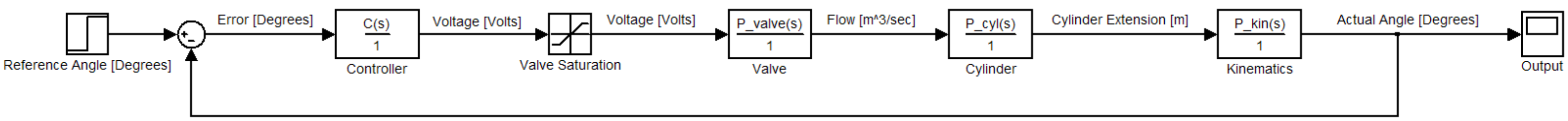


Figure 5 Block diagram of closed-loop position control of module rotation

In Figure 5, the valve saturator is to limit the voltage sent to the valve solenoids. The voltage sent to the solenoids should not exceed 21.6 V (according to the datasheet, this is the maximum voltage that can be applied to the solenoids) [3]. The valve operating curves are shown in Figure 6 below:

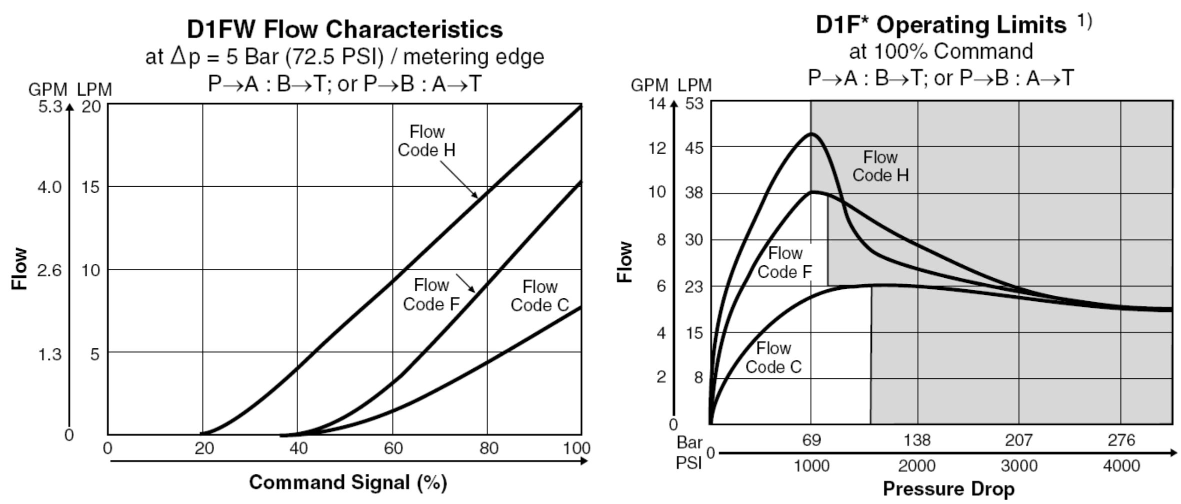


Figure 6 Valve operating curves. The valve used in the robot is "Flow Code C" [3].

In Figure 6, the first curve shows the relationship between flow and the percentage of the maximum command voltage (the maximum command voltage is 21.6 V) with a pressure drop of 72.5 psi. This curve changes depending on the pressure drop across the valve. Moreover, the pressure required in the cylinder changes depending on the transmission angle between the cylinders and the top plate. This is shown in Figure 7 below, which shows the maximum torque produced by the cylinders as a function of the rotation of the top plate. Furthermore, the pressure from the powerpack also varies depending on the current pressure in the accumulator. Before each movement, the accumulator is charged up to 1000 psi. Once the movement begins, the cylinders consume oil from the accumulator. Since the pump is not big enough to replenish the accumulator with oil at the same rate as the cylinders are consuming oil, there is a net decompression of the oil, and thus the pressure from the powerpack decreases. This was evident during testing, as the powerpack's pressure gauge is observed to drop from 1000 psi to nearly 0 for long movements.

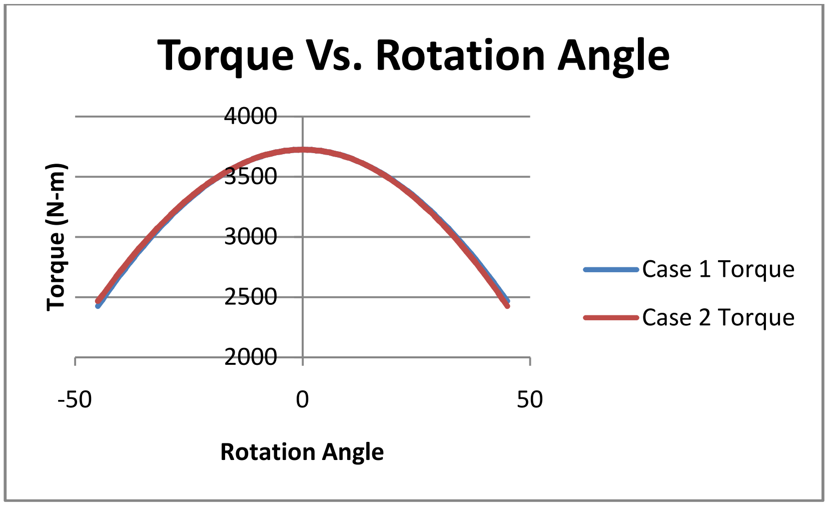


Figure 7 Torque as a function of rotation angle. The two cases correspond to whether the cylinder with the smaller transmission angle is pushing or pulling [1].

Therefore, for the robot, the pressure drops across the valves change for two reasons: (1) changing pressure demand at different transmission angles; and (2) insufficient supply from the powerpack. Since the flow vs. command signal relationship depends on the pressure drop, and the pressure drop is constantly changing, the transfer function of the valve is also constantly changing. In order to predictably control the system, feedback of the pressure drop (via pressure transducers) is required, and an adaptive controller needs to be designed which adapts to the changing pressure drop. Since this would be a project to itself, a simpler approach is taken: a controller is designed for the fastest system (corresponding to a 1000 psi pressure drop). This is a conservative approach, since the controller is designed for the largest possible pressure drop (as the pressure in the system is limited to 1000 psi), and the movement will only be slower if the pressure drop is less.

According to the Figure 6 above, the transfer function of the valve (corresponding to a pressure drop of 1000 psi) is:

$$P_{valve}(s) = \frac{Flow\ [\frac{m^3}{s}]}{Voltage\ [V]} = \frac{0.000333}{12.96} = 0.0000257$$

Equation 1

This transfer function assumes that the flow vs. command signal curve is linear. As shown in the figure above, the curve is roughly linear when the command signal is greater than 60% of the maximum command signal. Designing the controller for this region (the region greater than 60%) is a conservative approach since the slope of the flow vs. command signal curve is less steep in the region between 40% and 60% than in the region greater than 60%, and thus the modules will simply rotate more slowly if the command voltage is in this region. The valve has a deadband between 0 and 40% (whereby the valve outputs no flow). Therefore, a deadband compensator needs to be implemented. Although 40% of the maximum command signal corresponds to 8.64 V, the actual deadband that was measured during testing is 9.2 V. Therefore, a deadband compensator of 9.2 V is implemented. One possible reason for the difference between the actual deadband and that which is stated on the data sheet is that the op-amps output 0.5 V even when their input signal is 0 (as will be discussed in Section 9.2). This means that the solenoid which isn't energized (or rather, the one that shouldn't be energized) is still producing force on the valve's spool that is opposing the solenoid which is energized.

The cylinder's transfer function relates the flow from the valves to the extension of the cylinders by the equation V=Q/A (assuming incompressible flow), where V is the velocity of the piston, Q is the flow, and A is the cross-sectional area:

$$V = \frac{dl}{dt} = \frac{Q}{A}$$

Taking the Laplace transform, and assuming zero initial conditions:

$$sL(s) = \frac{Q(s)}{A}$$

$$P_{cyl}(s) = \frac{L(s)}{Q(s)} = \frac{1}{sA}$$

Noting that the oil must simultaneously fill the bore side of one cylinder and the rod side of the other:

$$A = A_{bore} + A_{rod-annular} = 0.002082\ m^2$$

Therefore,

$$P_{cyl}(s) = \frac{L(s)\ [m]}{Q(s)[\frac{m^3}{s}]} = \frac{1}{s(0.002082)} = \frac{480.3}{s}$$

Equation 2

Finally, a relationship is needed between cylinder extension and rotation of the modules. This relationship was developed in the design report to be:

$$P_{kin} = \frac{\theta\ [\text{Degrees}]}{\text{L [m]}} = 685$$

Equation 3

Combining these three transfer functions (Equations 1, 2, and 3), the transfer function of the entire plant (from command voltage to rotation) is:

$$P(s) = \frac{\theta(s)}{V(s)} = P_{valve} * P_{cyl} * P_{kin} = \frac{8.455}{s}$$

Equation 4

Since the plant has an integrator, it inherently has zero steady state error. Furthermore, the plant is only first order, which means that a proportional controller (without an integral or derivative term) would not increase the order of the system and thus would not cause overshoot (since first-order systems do not exhibit overshoot). As such, a tuneable proportional controller is implemented in LabVIEW.

It should be noted that this transfer function is the result of many assumptions. The fact that it is a transfer function of a mechanical system with inertia means that it should be at least second order. However, these simplifying assumptions are conservative and make it easier to design and tune the controller. Sure enough, testing revealed smooth, fast, and accurate movements, and thus increasing the complexity of the controller is unnecessary. Figure 8 below shows that the bottom module's response to a 45° step has a 0.84 second settling time and exhibits no overshoot.

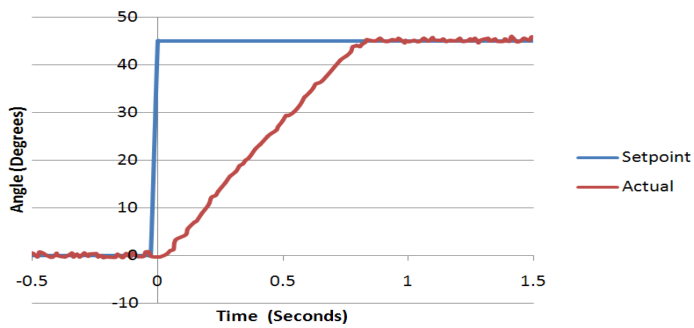


Figure 8 Bottom module's response to a 45° step command

A simulation of the step response is shown in Figure 9 below. The simulation has a faster settling time than the actual results shown in Figure 8 above, and also has a different velocity profile – the actual response has a nearly constant velocity profile, whereas the simulated response exhibits smoother acceleration and deceleration. Both of these differences between the actual and simulated response are signs that the powerpack is unable to meet the demand of the robot's movement, thus increasing the settling time and causing it to have constant velocity (limited by the pump's flow output). A flow saturator is not implemented in simulation due to the complexity of modeling the flow contribution of the accumulator. In any case, the fact that the simulation has a faster settling time than the actual system shows that, although the controller is simple, it is conservative and designed according to a worst-case scenario.

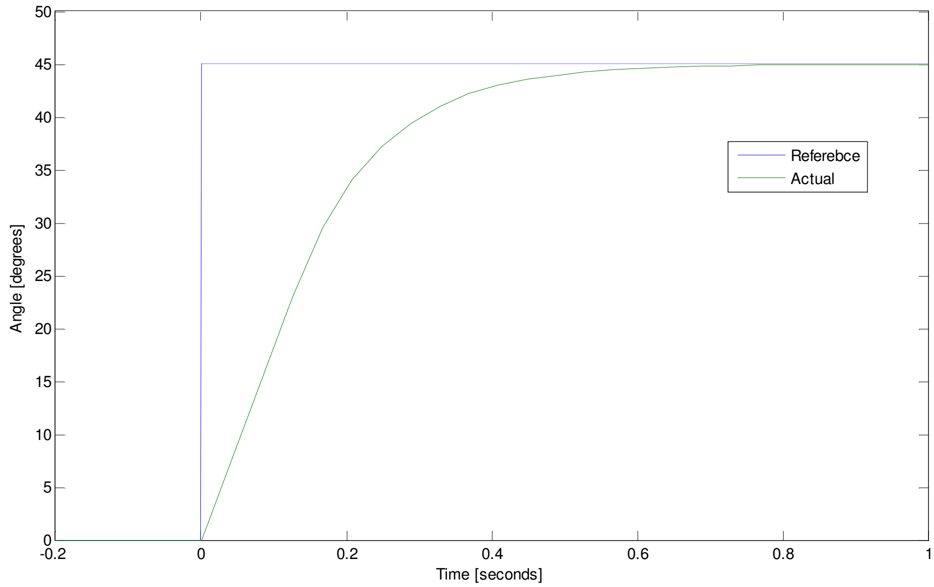


Figure 9 Simulation of step response to a 45° command.

VI. Software Design

The control software for the prototype is implemented in LabVIEW 7.1. It allows the user to operate in two modes: open-loop and closed-loop. In open-loop mode, the user controls the solenoid voltages directly. In closed-loop mode, the user specifies the bottom and top rotation, and the controller gain, and the modules automatically rotate to that position. The user can also specify the “Max Valve Command”, which limits the solenoid voltages. This is useful during testing to limit the speed of the movements. There is also a “Run Time” box in which the user can specify the time allotted for the current movement (this is only used in closed-loop mode). This is useful when the robot is to automatically perform a sequence of movements, such as in the design symposium. The “Run Time” should be long enough to complete the current movement and for the accumulator to fill in preparation for the next movement.

The software reads the potentiometers’ voltages from the DAQ card’s analog input pins, and outputs the solenoid command on the DAQ card’s analog output pins. Although each valve contains two solenoids, each solenoid shares a single analog output pin from the DAQ card. Therefore, a switch is used to select the appropriate solenoid for each valve (only one solenoid should be energized at any given time). Therefore, the software also outputs digital logic signals to the DAQ card’s digital pins (one logic signal for each switch). The value of this logic signal depends on the polarity of the command voltage specified by the user.

In summary, for each valve, the software outputs the absolute value of the valve’s command voltage to an analog output pin, and the switch logic signal to one of the digital pins (which determines which of the valve’s solenoid is energized). The value of the logic signal (1 or 0) depends on the polarity of the command voltage. This is illustrated in the Figure 10 below. The LabVIEW front panel and block diagram can be seen in Appendix B.

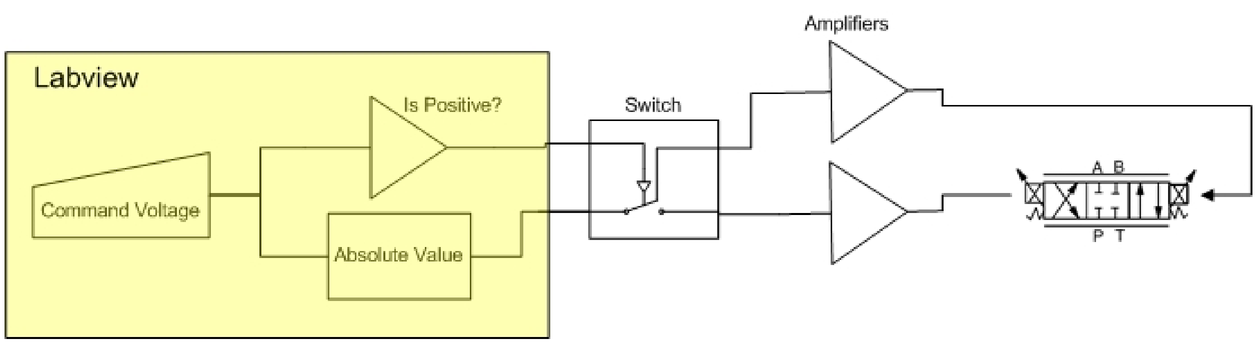


Figure 10 Logical flow diagram of system

VII. Schedule

Figures 11 and 12 below show the planned and actual Gantt charts, respectively, for manufacturing, electronics design and fabrication, controller and software design and testing, and systems testing. The main differences between the two charts are that manufacturing started slightly later than was planned due to some design changes, and that manufacturing of the four plates ended nearly one month later than was planned. Originally, the plates were to be manufactured by the author of this report. However, in mid-January, it was decided that Robert Wagner, a lab technician at the Department of Mechanical and Mechatronics Engineering at the University of Waterloo, would be responsible for manufacturing the plates. After this change, the plates were going to be completed by Feb. 23, 2009, but were not actually completed until nearly 3 weeks later on March 14, 2009. The reason for the delay in their completion is because Mr. Wagner was also busy with other projects.

However, since the plates were no longer being manufactured by the author, other parts of the project could be completed and tested while the plates were being manufactured, such as the software, controls, and electronics. Fortunately, although there was little time left between the completion of the plate's manufacturing and the design symposium, assembly of the modules occurred quickly since there were only few misalignments (which were non-critical and easy to fix), and only few flaws (which were also easy to fix) arose during testing. Those issues are discussed in the "Manufacturing" and "Testing" sections. Due to the fewer-than-expected number of issues, less time could be spent on assembly and testing than was originally planned, and the robot was completed and tested in time for the design symposium on March 23, 2009.

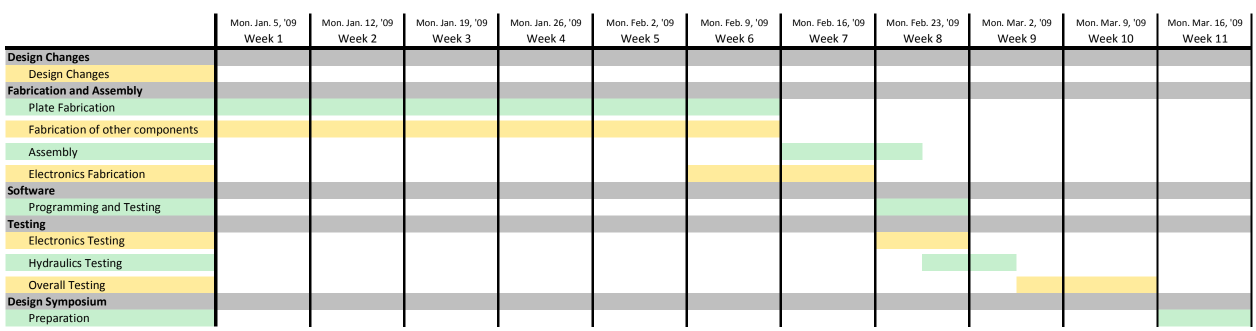


Figure 11 Planned Gantt chart

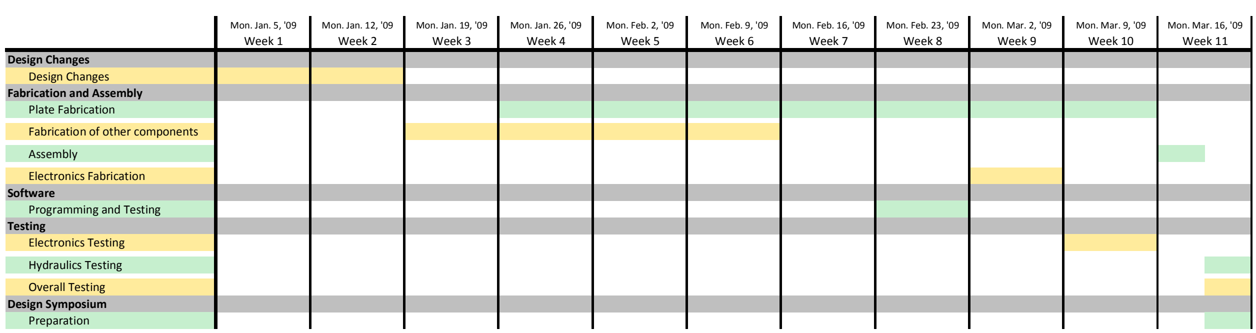


Figure 12 Actual Gantt chart

VIII. Issues during Fabrication and Assembly

The following issues arose during fabrication and assembly:

8.1 Limited Range of Rotation due to Cylinder Topping Out

When rotating the top plate, the cylinder that is extending would "top out" prematurely, and the cylinder that is contracting would still have quite a bit of stroke left when this occurred. This occurred at a rotation of 38°, which is much less than the 45° rotation that the modules were designed for. This problem was easily fixed by adding a ½" spacer underneath all of the cylinders so that the extending cylinder would no longer "top out" prematurely. Once the spacers were added, the maximum rotation of the top plate was 48°.

8.2 Misalignment between Gusset/Manifold Plate Bolt Holes

The holes on the gussets did not align with the holes on the base plate. This occurred since the bend radius used in SolidWorks is different from the actual bend radius. This problem was fixed by filing the holes until they aligned with the base plate.

8.3 Misalignment between Manifold and Valve Ports

The ports of the manifold plate of the bottom module and those of the valve do not align perfectly when the valve is mounted onto the plate. This causes a very small amount of oil to leak from under the valve of the bottom module (this issue is not present in the top module). Since this problem cannot be easily fixed, testing of the robot continued despite this small leak.

IX. Commissioning, Testing, and Results

Testing occurred in 4 stages:

1. First, the control software was tested.
2. Next, the electronic circuit was connected to the computer and tested along with the software.
3. Third, the hydraulic circuit was commissioned and tested.
4. Fourth, the overall system was commissioned and tested.

The following sub-sections describe the protocols used in commissioning and testing, as well as the test results.

9.1 Control Software testing

1. In open-loop mode, set a desired solenoid voltage, and ensure that the analog outputs of the DAQ card is $1/_{2.95}$ of that voltage (the amplifier gain is 2.95). Test this for several different voltages.
2. Also test that the digital switch signals change according to the polarity of the solenoid voltage.

Results: All worked as expected.

9.2 Electronics testing

1. Connect the circuit to the DAQ card (through the breakout board).
2. Power the circuit, and slowly increase the supply voltage from 0 to 24V.
3. In open-loop mode, set a solenoid voltage, and check that the outputs of the op-amps are the same as the desired voltage.
4. Check that the correct op-amps are being selected by the switch (according to the polarity of the desired voltage). For each valve, only one op amp should ever be outputting a voltage.

Results: The only issue is that the op-amps were outputting 0.5 V even if they weren't being selected by the switch. However, this is not a big issue since the valves have a deadband of 8.64 V (they do not produce any flow for signals between -8.64 and 8.64 V), and the closed-loop position control should compensate for this 0.5 V.

9.3 Hydraulics Commissioning and Testing

1. Connect the powerpack hoses to the ports on the sides of the bottom module.
2. Set the pressure on the pressure relief valve to 0.
3. On the top module, open the manual valve (thus opening the pump to the tank). Power the powerpack, and ensure that there are no leaks.
4. If there are no leaks, close the manual valve, and check again for leaks.
5. If there are no leaks, slowly increase the relief valve setting in 100 psi increments up to 1000 psi. At each setting, check for leaks.

Results: A small oil spill occurred at 1000 psi due to a loose fitting. Once this fitting was tightened, this test was repeated and a leak was detected in the bottom module between the manifold plate and valve.

This leak is due to misalignment between the port holes of the manifold plate and those of the valve, and cannot be fixed without re-fabricating the manifold plate. Therefore, testing continued despite this small leak.

9.4 Overall System Commissioning and Testing

1. Connect the potentiometers and solenoids to the electronic circuit.
2. Set the relief valve pressure to 100 psi.
3. Run the software in open-loop mode.
4. Slowly increase the solenoid voltages until the modules start to move.
5. If the modules moved in Step 4, calibrate the potentiometers by measuring the voltages at several angles and fitting a linear curve in Microsoft Excel. Once the curve has been calculated, adjust the potentiometers' scaling factors in the control software.
6. Run the control software in closed-loop mode.
7. Set the controller gain to be very small (e.g. 0.05) and the max valve command to be just above the deadband (e.g. 10.5 V).
8. Input a desired angle for each of the modules, and ensure that the modules move to that angle.
9. If the modules move to the angles smoothly, gradually increase the max valve command, controller gain, and system pressure (up to 1000 psi) in order to optimize the performance.

Results: Open-loop mode worked right away. Closed-loop mode revealed a couple minor bugs in the control software. However, within 2 hours, closed-loop mode was also working. The optimal gain (in terms of response time, smoothness, and noise rejection) is found to be 0.5. Figure 13 below shows the step response of the bottom module with a gain of 0.5.

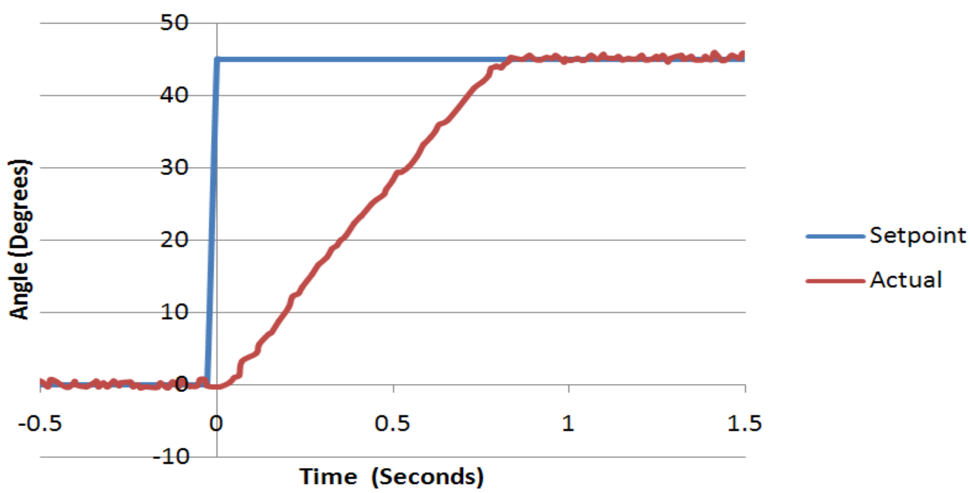


Figure 13 Bottom module's response to a 45° step command

X. Budget

Table 1 below shows the estimated costs for each module. Note that these costs are estimated, since the components for this project are sponsored by Parker-Hannifin, MP Filtri Canada, and the Department of Mechanical and Mechatronics Engineering (MME) at the University of Waterloo, and thus the exact costs are not known by the author. The total cost per module is estimated to be $1286. Since the prototype consists of two modules, the total cost for the prototype is $2572. This figure is slightly higher than the one provided in the design report (which estimated $1192). The main reason for the discrepancy between the total cost that was estimated in the design report and the one estimated here is that the design report did not include the costs of the electronics. Note that these costs do not include the equipment which is shared by all modules, such as the hydraulic powerpack, the computer, and the power supply (which are also provided by MME).

Category	Component	OEM or Supplier	Part#	Cost	Qty	Net Cost
Hydraulics	Hydraulic cylinders (1.5" bore, 5" stroke, 5/8" rod)	Parker	1.5" BB - 3L C T 1 4 A 3"	$200	2	$400
	Female Rod Clevis for Cylinders	Parker	50940	$10	2	$20
	Mount for Cylinder Clevises	Parker	69195	$10	4	$40
	Hydraulic proportional directional valves	Parker	D1FW E09 C C N J 0	$500	1	$500
	Fittings, Hoses, and Plugs	Industrial Hydraulics & Pneumatics		$200	1	$200
Electrical	Rotary potentiometer	ECE Store		$15	1	$15
	Analog Switch	Digikey	Maxim DG419	$5	1	$5
	Power Op Amps	Motion Industries Canada	TI OPA548	$13	2	$26
	Electrical Auxillery (Hoses, etc...)			$10	1	$10
Materials	Materials	UW Engineering shop supply store		$70	1	$70
Total Cost						**$1,286**

Table 1 Estimated costs for each module

XI. Operating Procedures

This section outlines a few operating procedures that must be followed to ensure the safe operation of the robot:

11.1 Pressure Discharge

The system can store pressure in two ways when it is powered off: within the accumulator and within the cylinders. Pressure is stored within the accumulator if the pressure lines are closed from the return lines. Pressure remains in the cylinders after power-off since the valves are closed-center, meaning that all ports are blocked when the solenoids aren't energized (the solenoids are spring-return). Although this feature of the valves means that the robot arm is fail-safe in case of electrical power failure (since incompressible oil would remain trapped in the cylinders and thus the robot arm would remain in its position, even if it is under load), it can also pose a danger if maintenance were to be performed on the valve, the actuators, or the hoses between the valves and the actuators. The following procedure discharges all the pressure in the system, and it should be performed anytime adjustments are to be performed on the robot arm (such as adjusting a hose or adding/removing a module) or if the robot is going to be turned off for an extended period of time:

1. Turn the hydraulic powerpack off (if it is not already off).
2. Discharge the accumulator pressure by fully opening the adjustable throttle valve attached to the accumulator.
3. Discharge the pressure in the pressure lines by slowly opening the manual valve on the top module.
4. To discharge the pressure in the cylinders, turn the electrical power supply on, run the control software in "Open-Loop", and apply the maximum voltage (21.6 V) to each valve in both directions (21.6 and -21.6 V). In each direction, wait for about 30 seconds.
5. To ensure pressure in the pressure lines have been discharged, check that the pressure gauges and the powerpack show zero pressure. NOTE: This does not correspond to the pressure in the cylinders; it only measures the pressure in the pressure lines.
6. To ensure pressure in the cylinders has been relieved, fully open the valves (using Step 3 above), and try to manually rotate the modules. This may take a bit of effort due to the large friction of the cylinder seals.

11.2 Pressure Setting

The cylinders are rated up to 2000 psi, and the pressure filter is rated up to 1000 psi. Therefore, the system pressure should never exceed 1000 psi. This needs to be controlled at the powerpack. The following procedures describe how to set the maximum pressure with the powerpack used in this project. Of course, the procedures would change should a different powerpack be used.

1. Turn the hydraulic powerpack off (if it is not already off).
2. Turn the electrical power supply off (it is not already off).
3. The pressure relief valve on the powerpack has adjustable setting (by controlling the spring stiffness). Turn the hex screw fully counter-clockwise to set it to zero pressure.

4. Open the manual valve on the top module.
5. Turn the powerpack on. The flow meter should show full flow and the pressure gauge should read zero.
6. Slowly close the manual valve on the top module. The pressure gauge on the powerpack should still read zero, but now the flow meter should also read zero since all of the flow should be going through the pressure relief valve.
7. While carefully monitoring the pressure gauge on the powerpack, *slowly* increase the pressure setting on the pressure relief valve by turning the hex screw clockwise. Stop turning the screw once the pressure has reached the desired maximum pressure (which is not to exceed 1000 psi).

11.3 System Flushing

If the robot has not been used in a while, it is necessary to flush the hydraulic conduits in order to remove dirt and air. To flush the system, simply open the manual valve on the top module and run the pump for a couple minutes. To flush the cylinders, close the manual valve and rotate each module in both directions, either in open-loop or closed-loop mode.

XII. Conclusions

As mentioned in the introduction of this report, this project is deemed to be a success. The goals, which were initially thought to be impossibly ambitious, were successfully accomplished in time for a very impressive exhibit at the design symposium on March 23, 2009, where the robot arm ran non-stop throughout the entire symposium, completing nearly 2,000 movements.

Due to the relatively small number of issues encountered in fabrication, assembly, and testing, the design is also deemed to be good.

The prototype met all of the requirements set forth at the beginning of the project with regards to safety and ease of re-configuration. Furthermore, the prototype met all of the constraints; although the constraint regarding each module's payload has not been tested, that constraint should also be met according to theoretical calculations.

XIII. Recommendations

Several recommendations are suggested regarding the design of the modules:

13.1 Using SAE Threads Instead of NPT Threads

Since NPT connections are more likely to leak than are SAE connections [2], one recommendation is to replace all of the NPT ports in the manifold plates with SAE ports. The reason NPT ports are used instead of SAE ports is that the University of Waterloo (which is where the prototype was fabricated) does not have SAE taps.

13.2 Using Dowel Pins

The alignment of two modules can be improved by using dowel pins. Currently, the modules are aligned with sheet guides that are screwed onto the sides of the top plate. This means that the modules are aligned with respect to their overall (outside) dimensions of the top plate, which have looser tolerances than the other features on the plate. These looser tolerances mean that there is greater possibility of misalignment between the two modules. Fortunately, this did not occur in the prototype (as is evident by no observed leaks between the top plate of the bottom module and the base plate of the top module). Nonetheless, It would be a good design change to replace the sheets with dowel pins in order to reduce the possibility of leaks between modules for future modules.

13.3 Increasing the Number of Degrees of Freedom of Each Module

Since each module only provides one degree of freedom, the robot arm has limited mobility. To be useful, the entire robot arm would likely have to be mounted on a rotary base in order to improve its reach. A better design would increase the number of degrees of freedom in each module. This can be accomplished, for example, by adding a rotary base at the bottom of each module. However, transmitting oil through this rotary base would be very challenging.

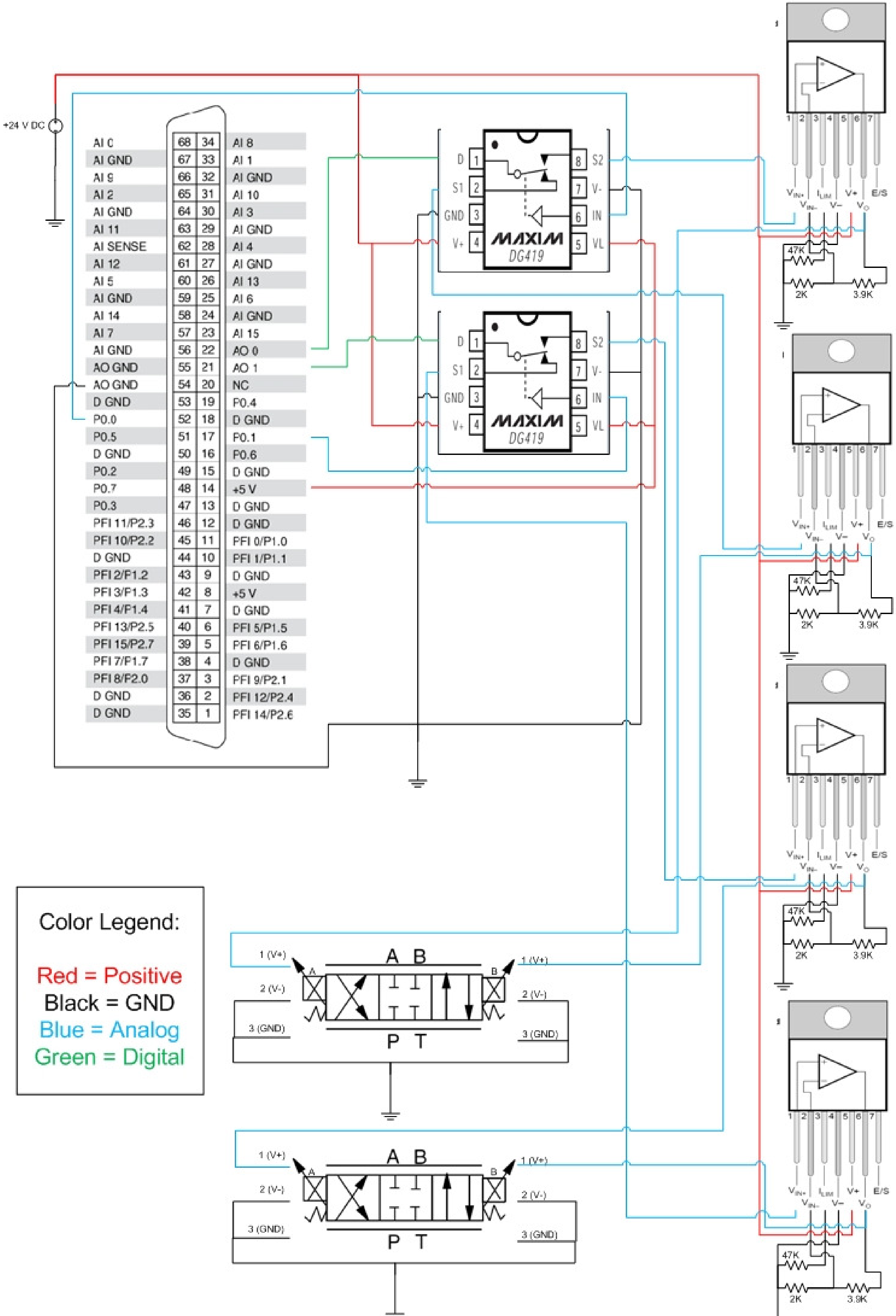
Another design would be to get rid of the shaft and to instead use three independent cylinders that are attached to the plates with ball joints. The design discussed in this report uses two cylinders that both produce torque about the same shaft. Therefore, the movement of the two cylinders are dependent on one another and only add one degree of freedom. By instead using three, independent cylinders, the cylinders are essentially producing three points in space that constrain the plane of the top plate relative to the plane of the base plate. Therefore, each module would now add three degrees of freedom to the robot arm, and the robot arm would have much greater mobility and reach. This design was considered in the initial design of the modules, but was not pursued mainly due to its cost. In order to control the position of the modules, it would require the sensing of the position of the piston within each cylinder. Although there are off-the-shelf solutions for this (that use linear variable displacement transducers (LVDT) or sonar), they are much too expensive for use in this project. To further add to the cost, since each cylinder is now independent, each module would also require three valves (one for each cylinder). This not only adds to the cost but also the size of the modules (however, the increased size may be justified by the increased mobility of each module).

XIV. References

1. Alnaif, A. “Hydrabot: The Modular Electro-Hydraulic Robot Arm – Design Report”, 2008. [Online] Available: http://www.eng.uwaterloo.ca/~aalnaif/ [Accessed: April 4, 2009]
2. Esposito, A. (2003). *Fluid Power with Applications*. 6th ed. Columbus: Prentice Hall.
3. Parker-Hannifin Corporation. “Data Sheet for Hydraulic Proportional Directional Valve”. [Online] Available: http://www.parker.com/literature/Hydraulic%20Valve%20Division/hydraulicvalve/Catalogs-Bulletins/MASTER%20HVD%20Catalogs/Cat%20HY14-2550_1-07/HY14-2550a001.pdf [Accessed: April 4, 2009]

Appendix A – Electrical Schematic

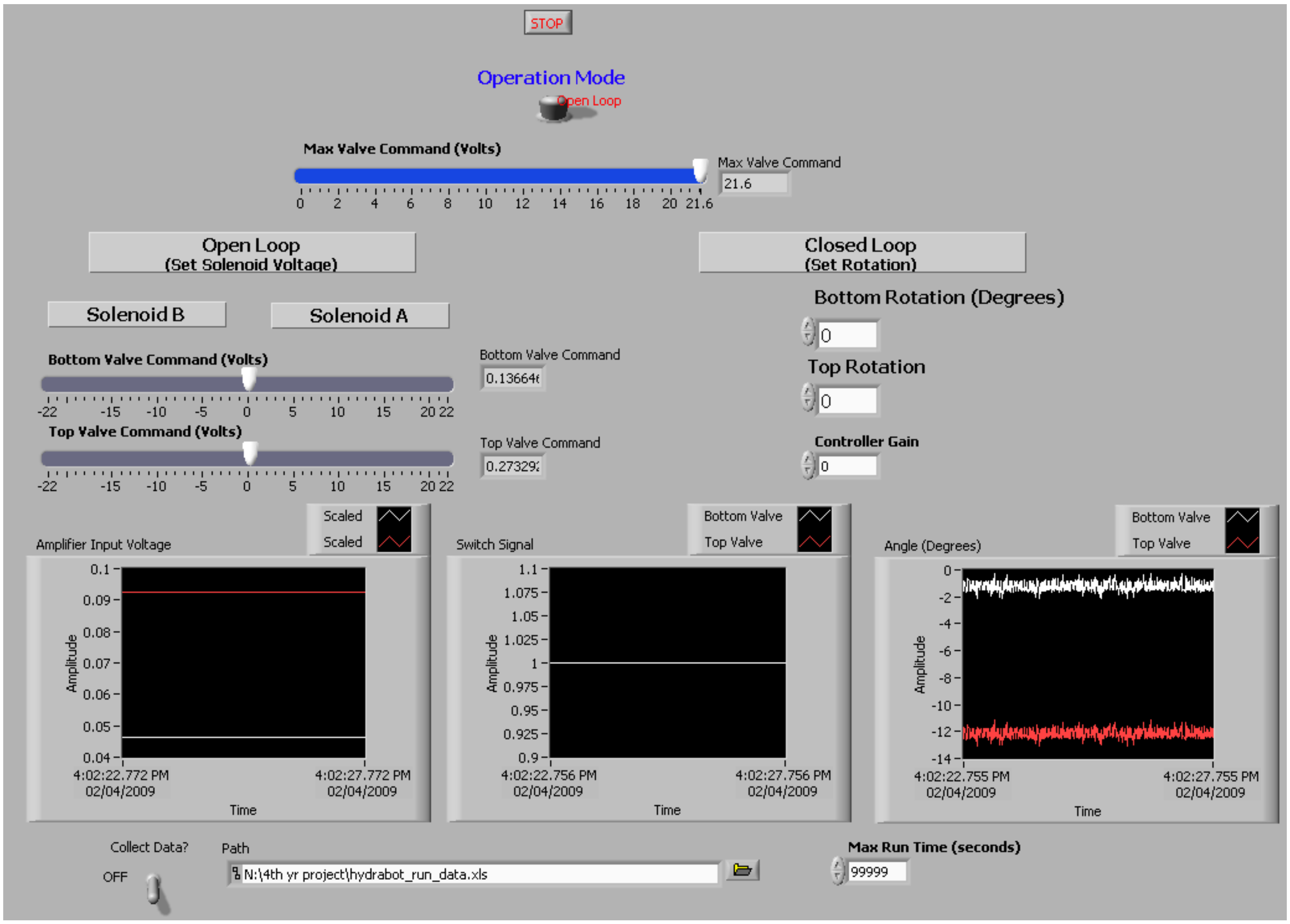
(on next page)



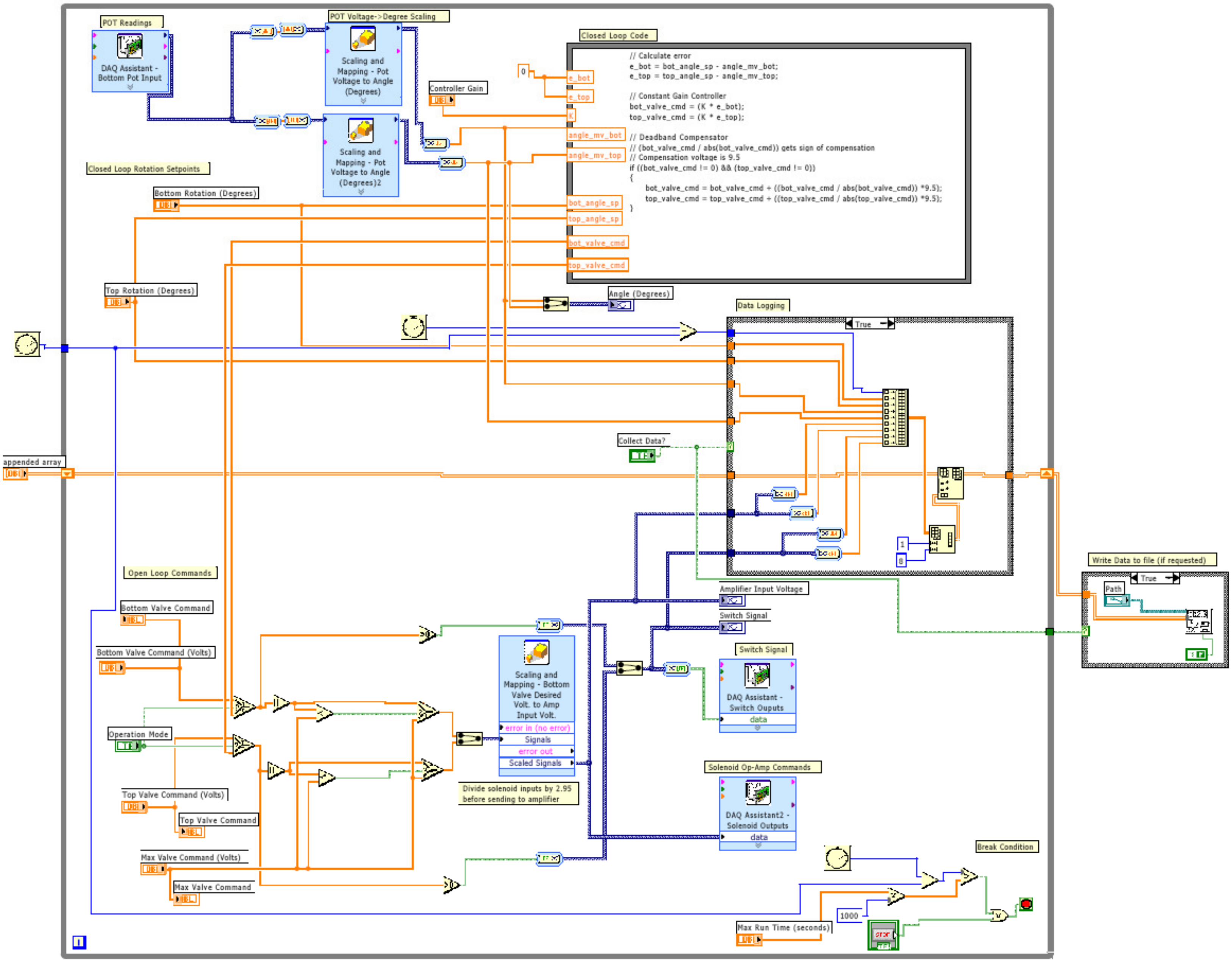
+24 V DC
AI 0
AI GND
AI 9
AI 2
AI GND
AI 11
AI SENSE
AI 12
AI 5
AI GND
AI 14
AI 7
AI GND
AO GND
AO GND
D GND
P0.0
P0.5
D GND
P0.2
P0.7
P0.3
PFI 11/P2.3
PFI 10/P2.2
D GND
PFI 2/P1.2
PFI 3/P1.3
PFI 4/P1.4
PFI 13/P2.5
PFI 15/P2.7
PFI 7/P1.7
PFI 8/P2.0
D GND
D GND
68 34
67 33
66 32
65 31
64 30
63 29
62 28
61 27
60 26
59 25
58 24
57 23
56 22
55 21
54 20
53 19
52 18
51 17
50 16
49 15
48 14
47 13
46 12
45 11
44 10
43 9
42 8
41 7
40 6
39 5
38 4
37 3
36 2
35 1
AI 8
AI 1
AI GND
AI 10
AI 3
AI GND
AI 4
AI GND
AI 13
AI 6
AI GND
AI 15
AO 0
AO 1
NC
P0.4
D GND
P0.1
P0.6
D GND
+5 V
D GND
D GND
PFI 0/P1.0
PFI 1/P1.1
D GND
+5 V
D GND
PFI 5/P1.5
PFI 6/P1.6
D GND
PFI 9/P2.1
PFI 12/P2.4
PFI 14/P2.6
D
S1
GND
V+
S2
V-
IN
VL
MAXIM
DG419
1 2 3 4 5 6 7
VIN+
VIN-
ILIM
V-
V+
VO
E/S
47K
2K
3.9K
Color Legend:
Red = Positive
Black = GND
Blue = Analog
Green = Digital
1 (V+)
2 (V-)
3 (GND)
A B
P T

Appendix B – LabVIEW Design

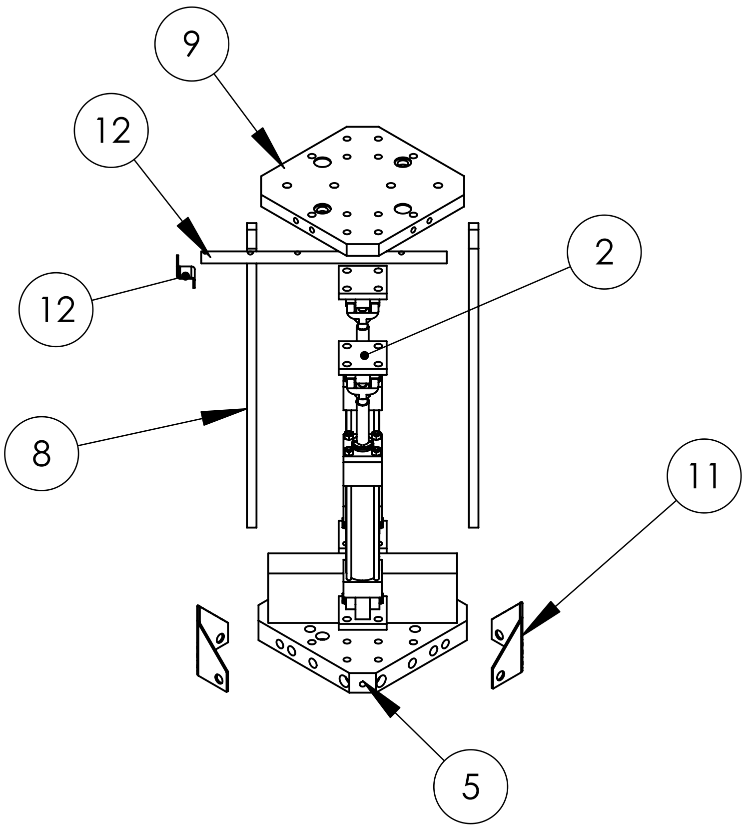
Front Panel (user interface):



Block Diagram:



Appendix C – Engineering Drawings



ITEM NO.	PART NUMBER	QTY.
2	Parker Cyl. Assy.	2
5	Base Plate	1
6	Shaft	1
8	Support Posts	2
9	Top Plate	1
11	Gusset	2
12	Potentiometer Panel	1

UNLESS STATED OTHERWISE: DIMENSIONS ARE IN mm TOLERANCES: +/- 0.2 mm		NAME	DATE	University of Waterloo
	DRAWN	Abed Alnaif	4/6/09	Full Assembly (Exploded)
	CHECKED			
	ENG APPR.			
	MFG APPR.			
MATERIAL	Q.A.			
FINISH --	COMMENTS:			SIZE A — DWG. NO. 1 — REV. 1
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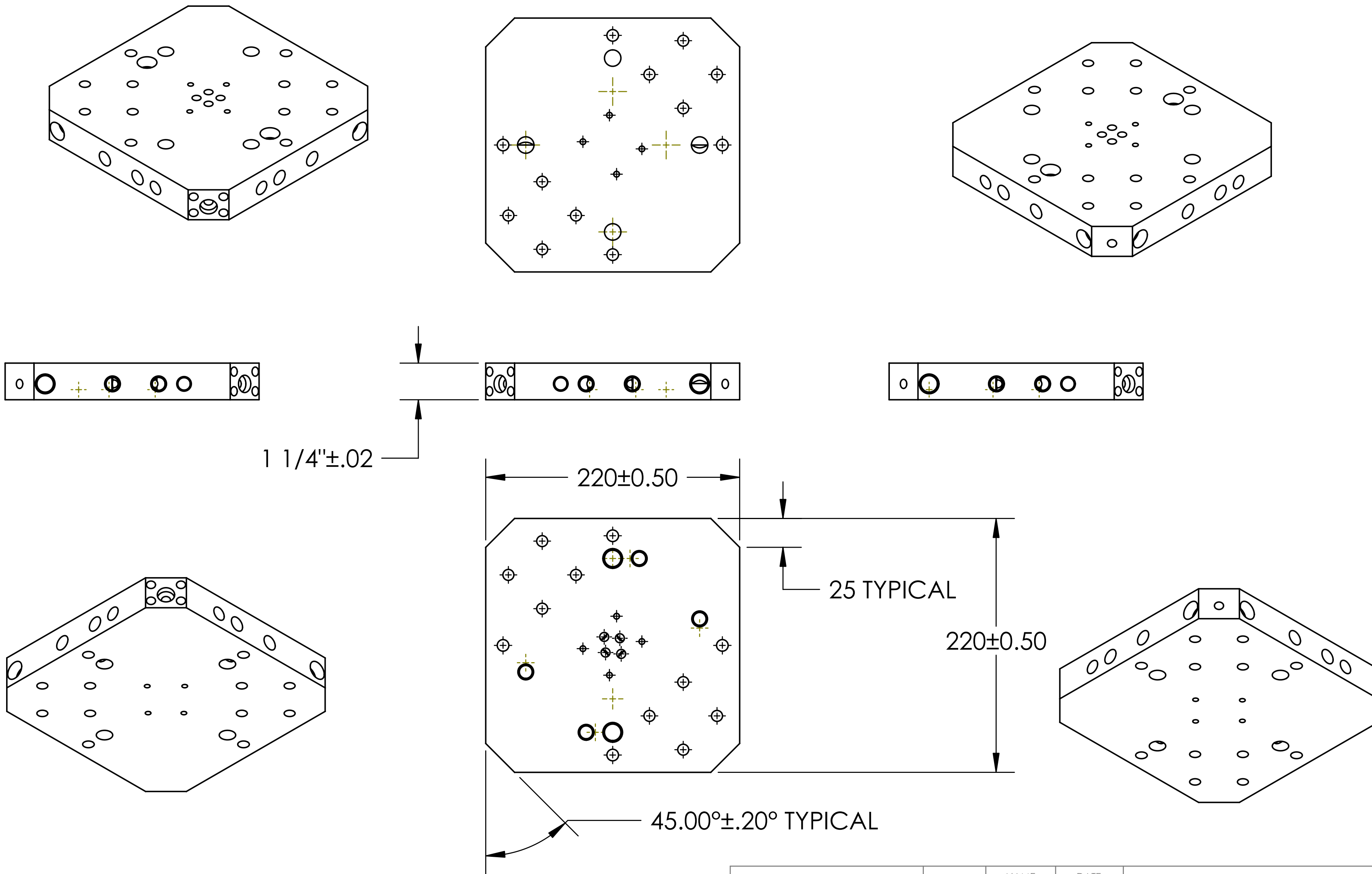

Note:
All surfaces need to be skinned so that they are flat and smooth in order to prevent oil leaks.

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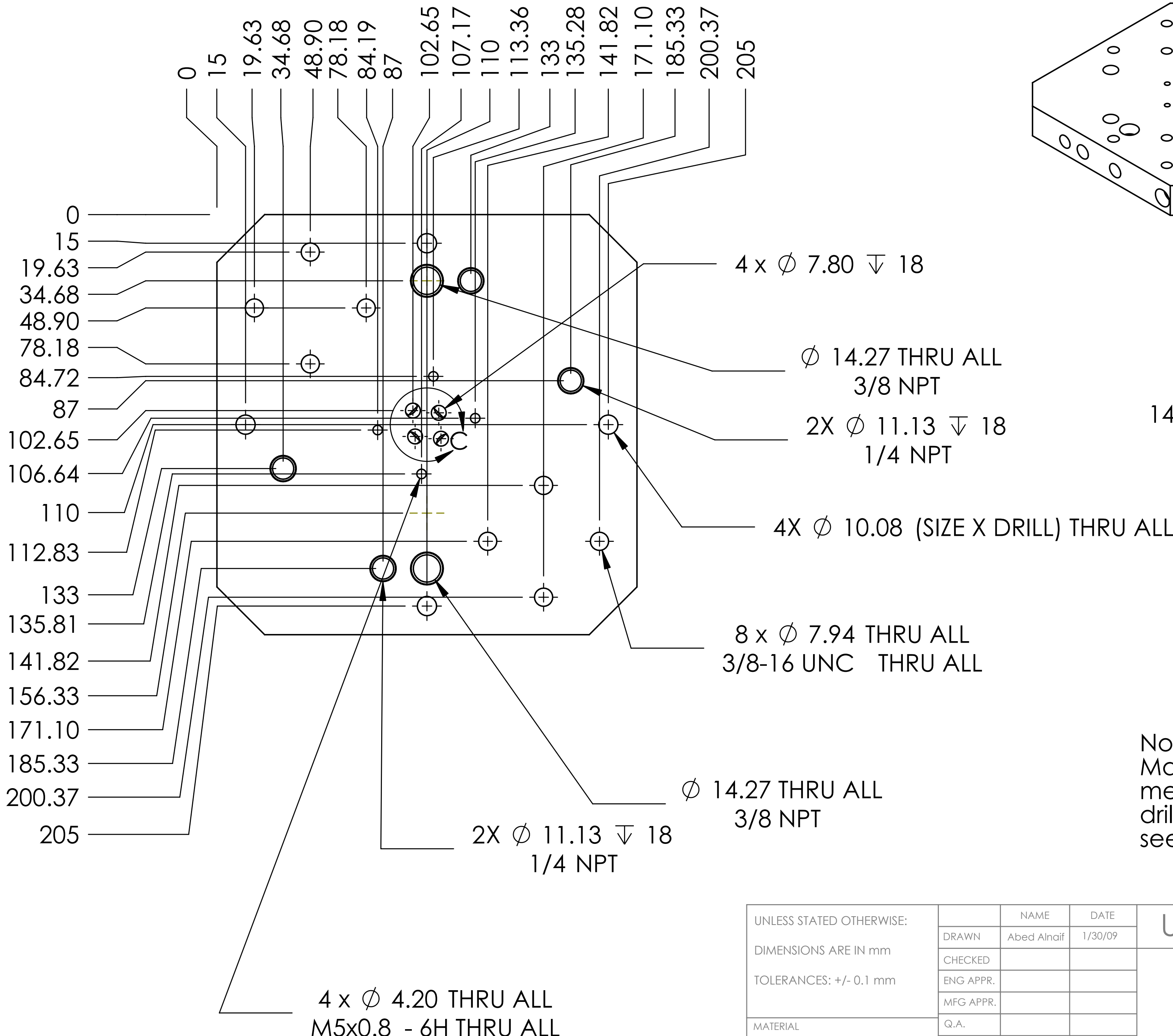
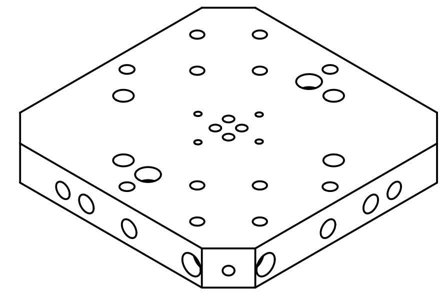
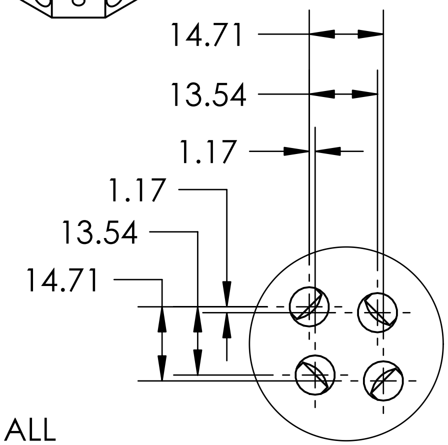
	DRAWN	Abed Alnaif	1/30/09	
	CHECKED			Base Plate (Overall Dimensions)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. 5 REV. 3
				SCALE 1:5 WEIGHT: SHEET 1 OF 5







DETAIL C
SCALE 2 : 3

Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)

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	CHECKED			Base Plate (Top View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
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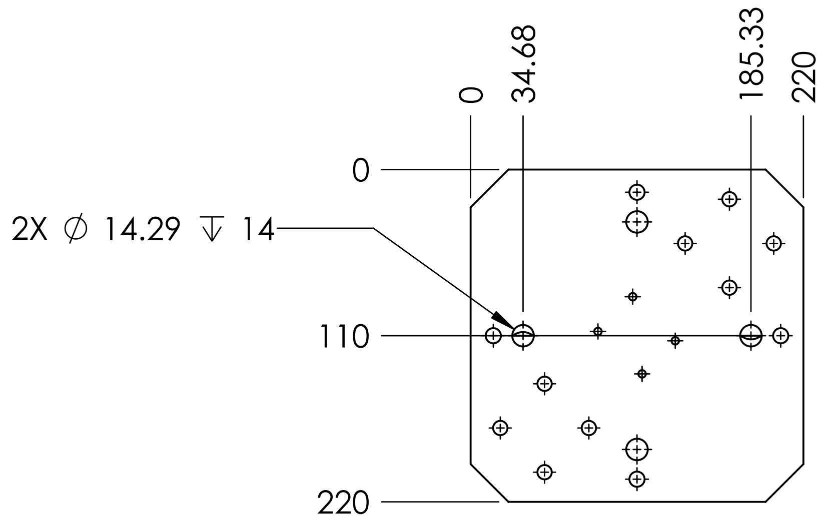
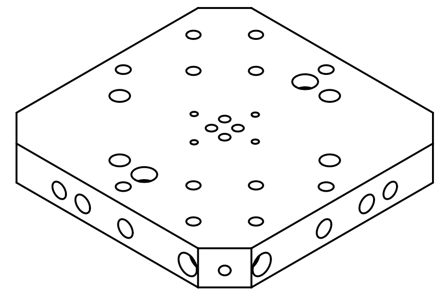
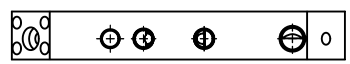
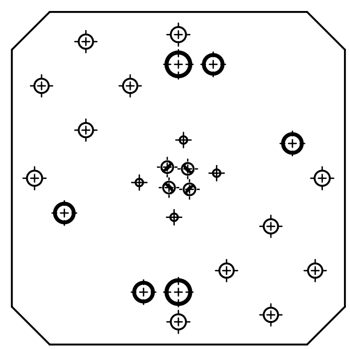
				SCALE 1:3 — WEIGHT: — SHEET 2 OF 5









Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)

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	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
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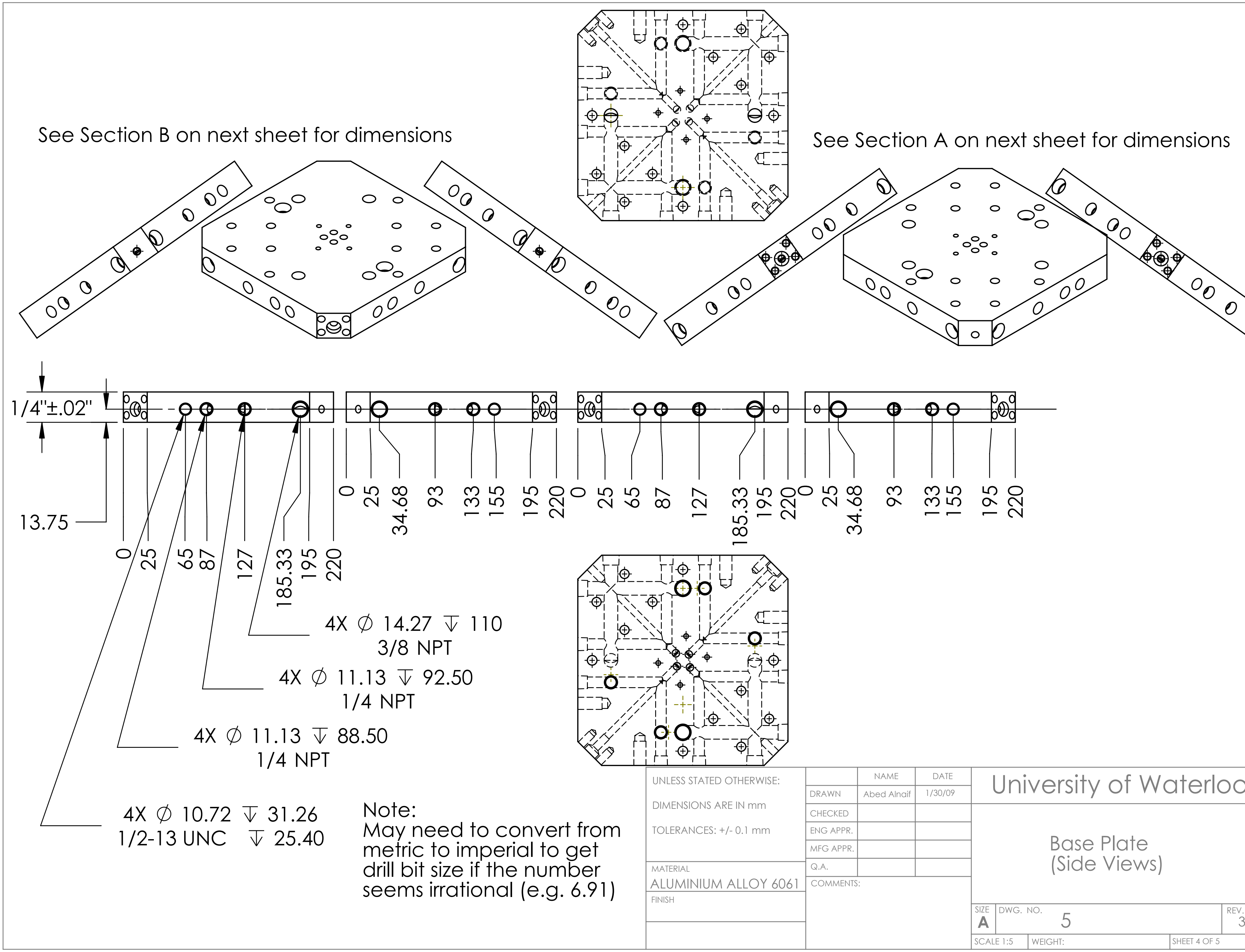

See Section B on next sheet for dimensions
See Section A on next sheet for dimensions
1 1/4"±.02"
13.75
0
25
65
87
127
185.33
195
220
0
25
34.68
93
133
155
195
220
0
25
65
87
127
185.33
195
220
0
25
34.68
93
133
155
195
220
4X ∅ 14.27 ↧ 110
3/8 NPT
4X ∅ 11.13 ↧ 92.50
1/4 NPT
4X ∅ 11.13 ↧ 88.50
1/4 NPT
4X ∅ 10.72 ↧ 31.26
1/2-13 UNC ↧ 25.40
Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)
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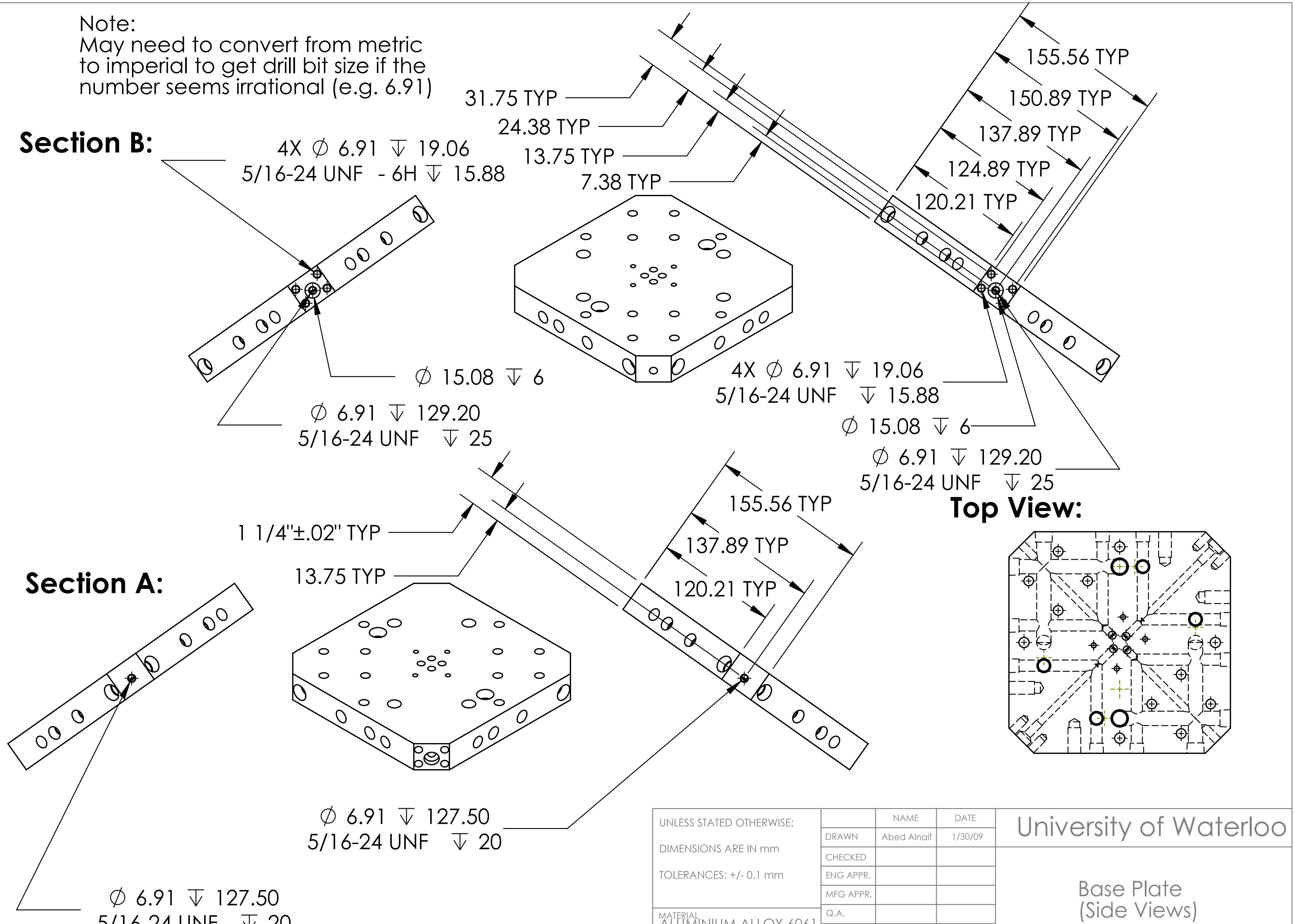
DIMENSIONS ARE IN mm
TOLERANCES: +/- 0.1 mm
MATERIAL
ALUMINIUM ALLOY 6061
FINISH
NAME
DATE
DRAWN
Abed Alnaif
1/30/09
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
University of Waterloo
Base Plate
(Side Views)
SIZE
A
DWG. NO.
5
REV.
3
SCALE 1:5
WEIGHT:
SHEET 4 OF 5

Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)



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TOLERANCES: +/- 0.1 mm	CHECKED			Base Plate (Side Views)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
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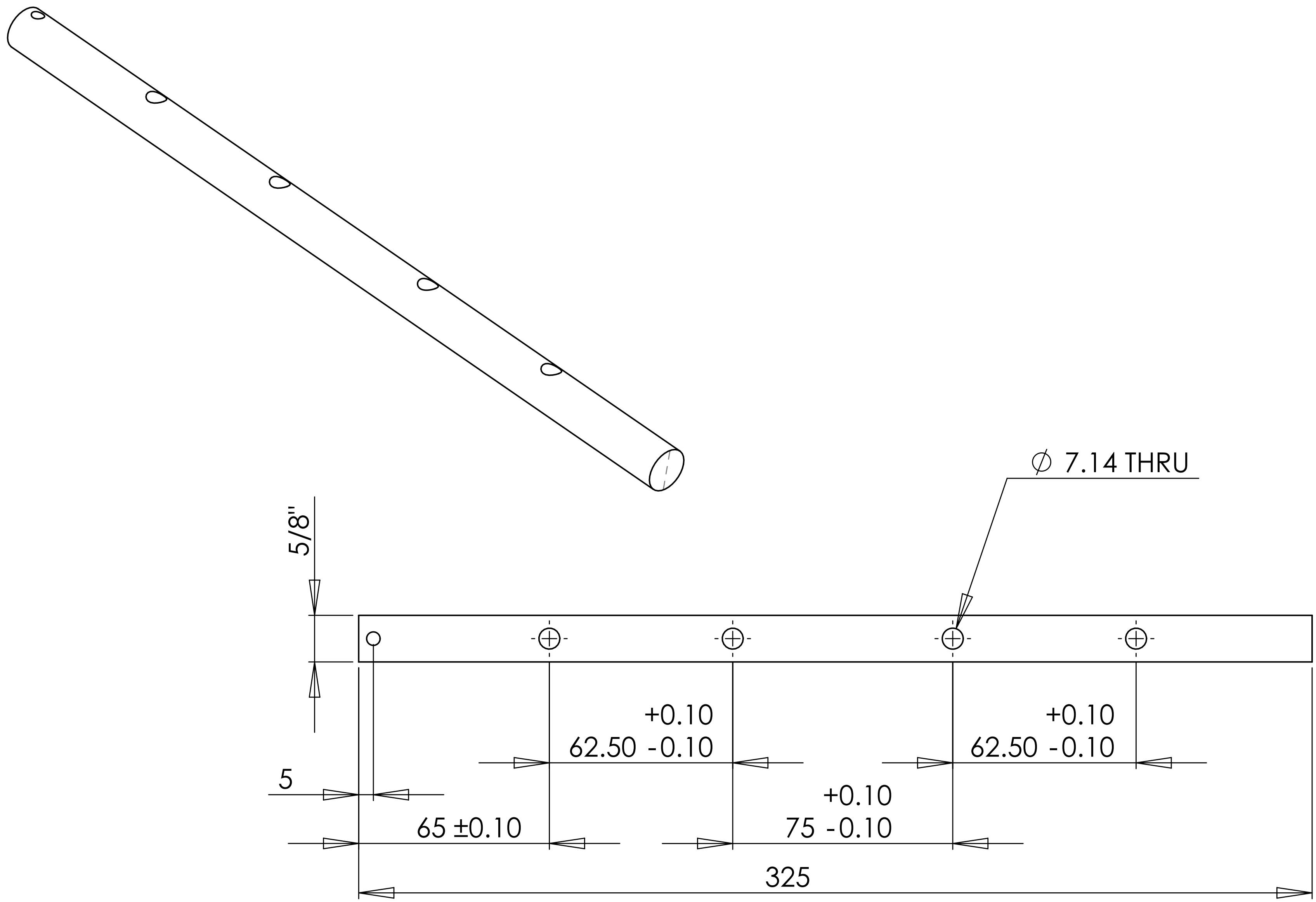
				SCALE 1:5 WEIGHT: SHEET 5 OF 5



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TOLERANCES: +/- 0.2 mm	CHECKED			Shaft
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINUM ALLOY	Q.A.			
FINISH --	COMMENTS:			
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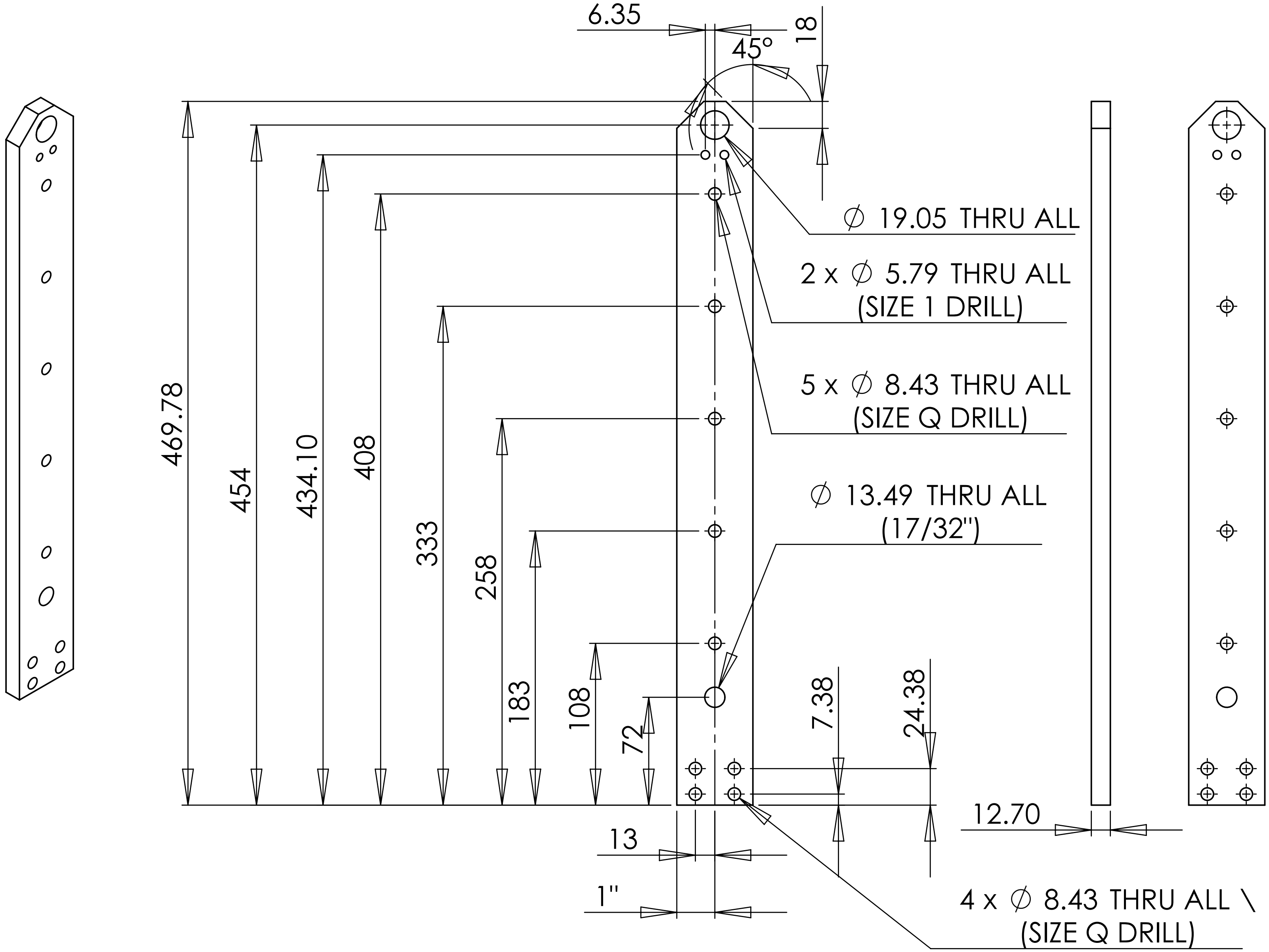

UNLESS STATED OTHERWISE: DIMENSIONS ARE IN mm TOLERANCES: +/- 0.2 mm		NAME	DATE	University of Waterloo
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	CHECKED			
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINUM ALLOY 6061	Q.A.			
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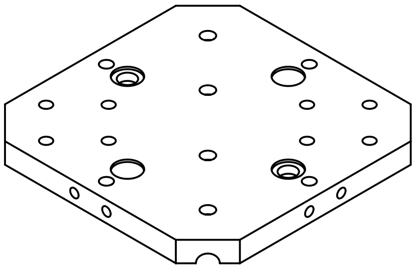
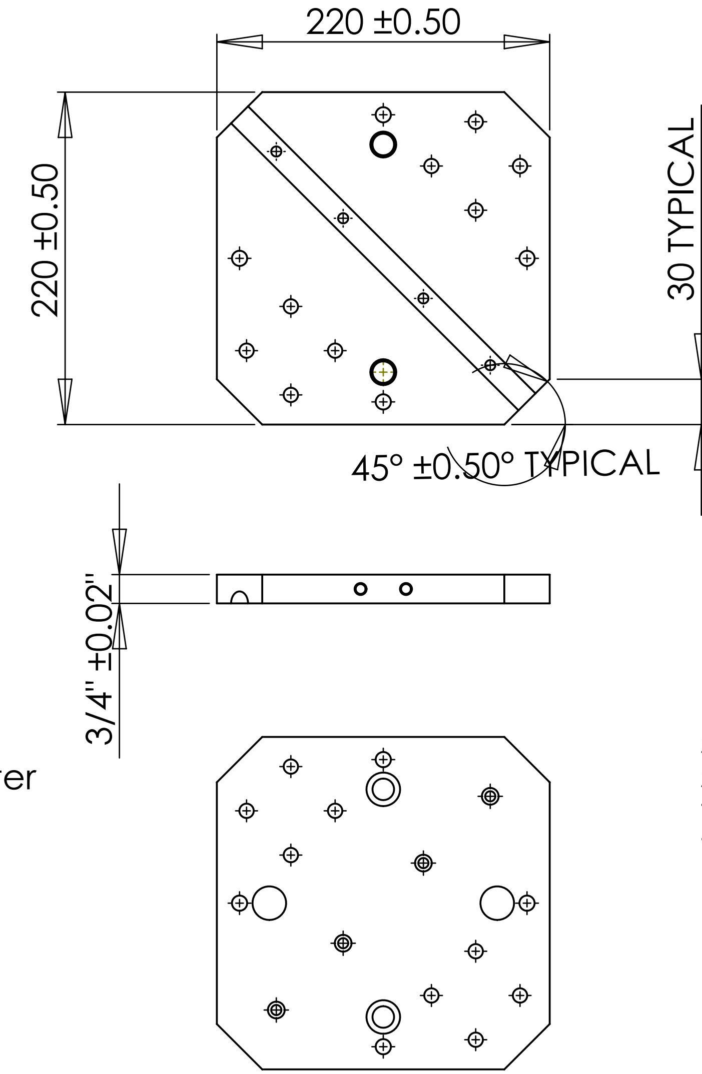
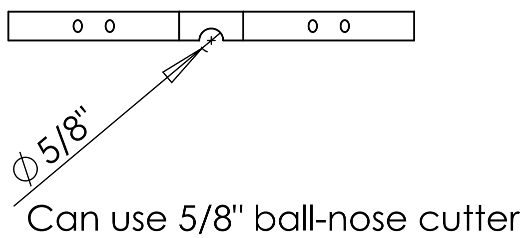
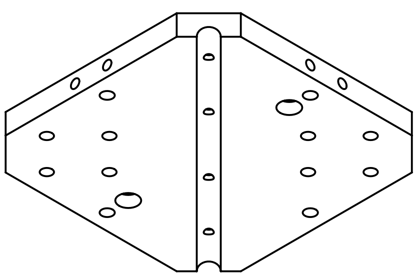
				SCALE 1:4 WEIGHT: SHEET 1 OF 1







Notes:
1. Top and bottom surfaces need to be skinned so that they are flat and smooth in order to prevent oil leaks.



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TOLERANCES: +/- 0.1 mm	CHECKED			Top Plate (Overall Dimensions)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
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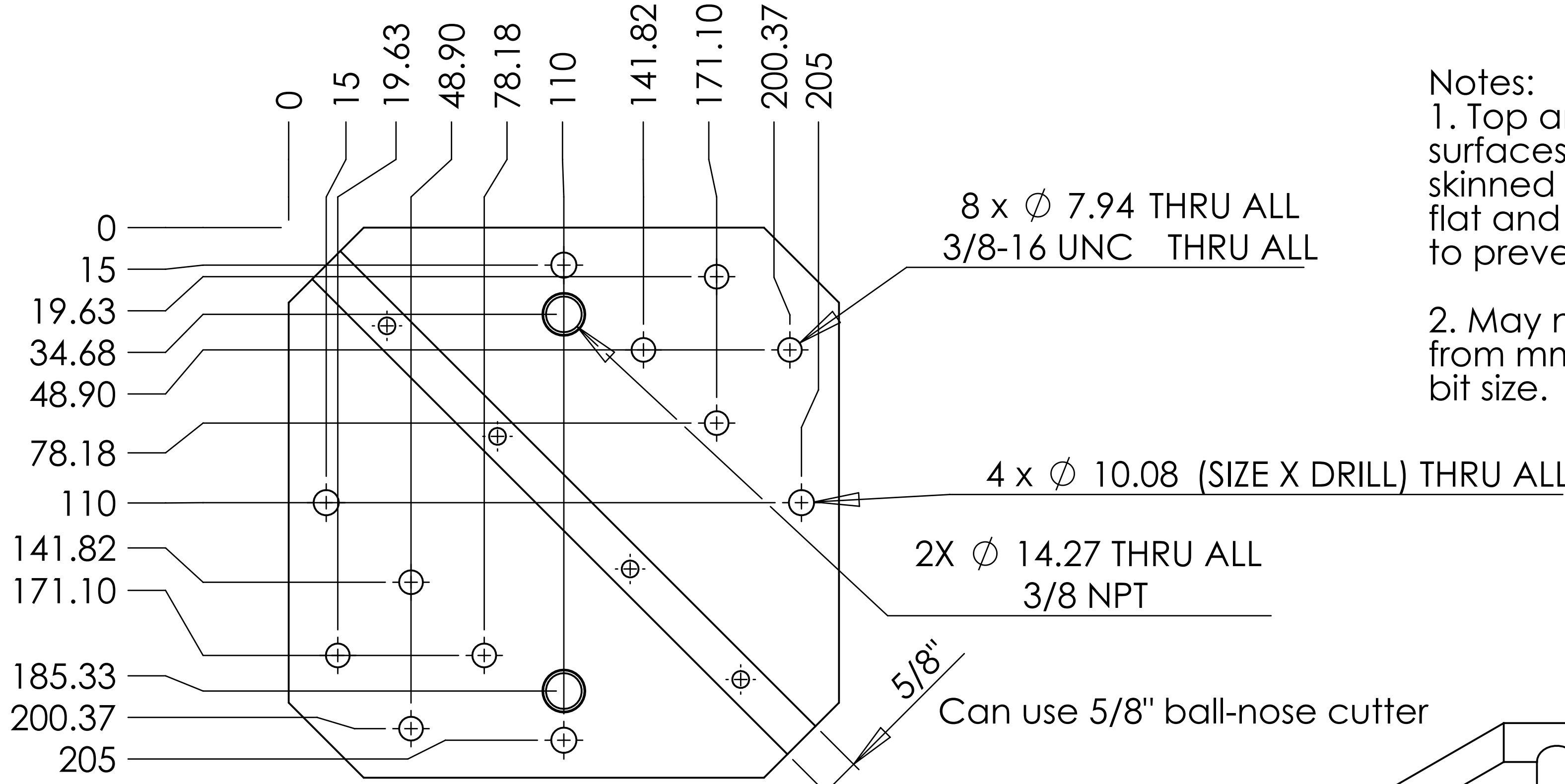
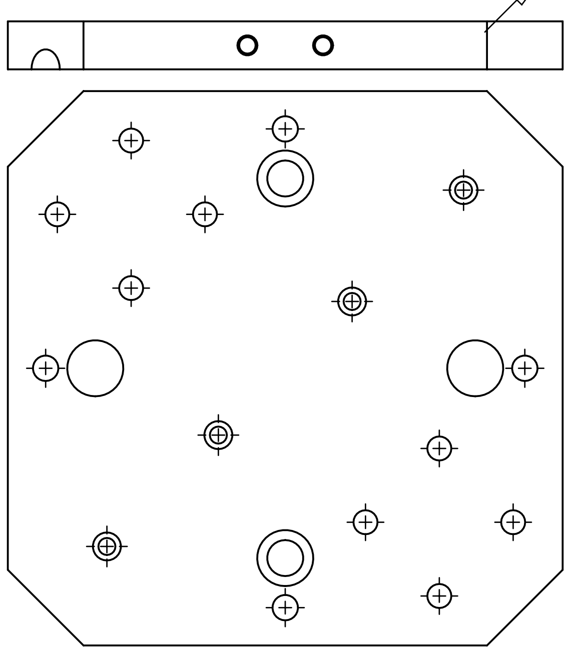
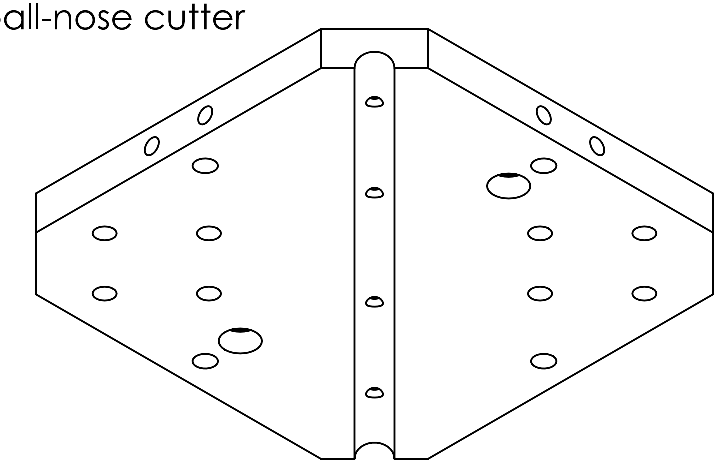


Notes:
1. Top and bottom surfaces need to be skinned so that they are flat and smooth in order to prevent oil leaks.

2. May need to convert from mm to in. to get drill bit size.





UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/13/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Top Plate (Bottom View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
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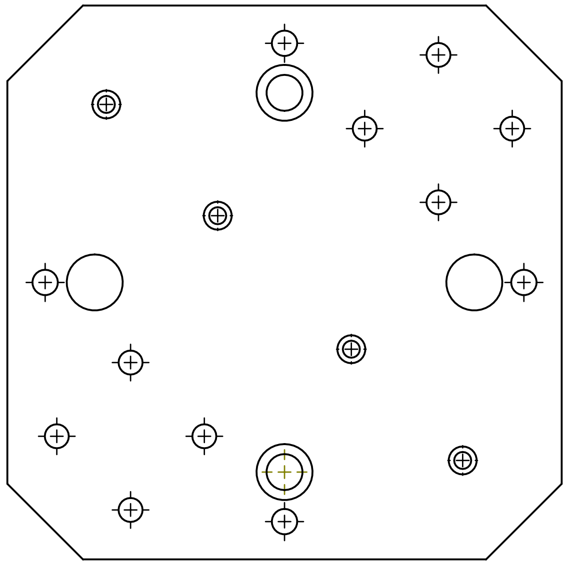
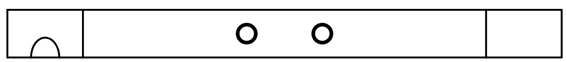
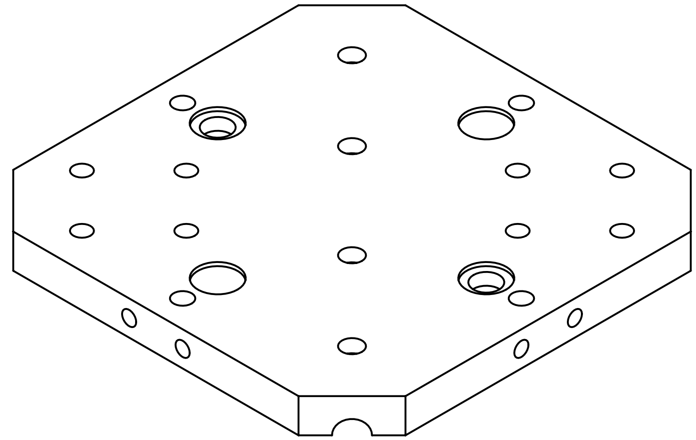
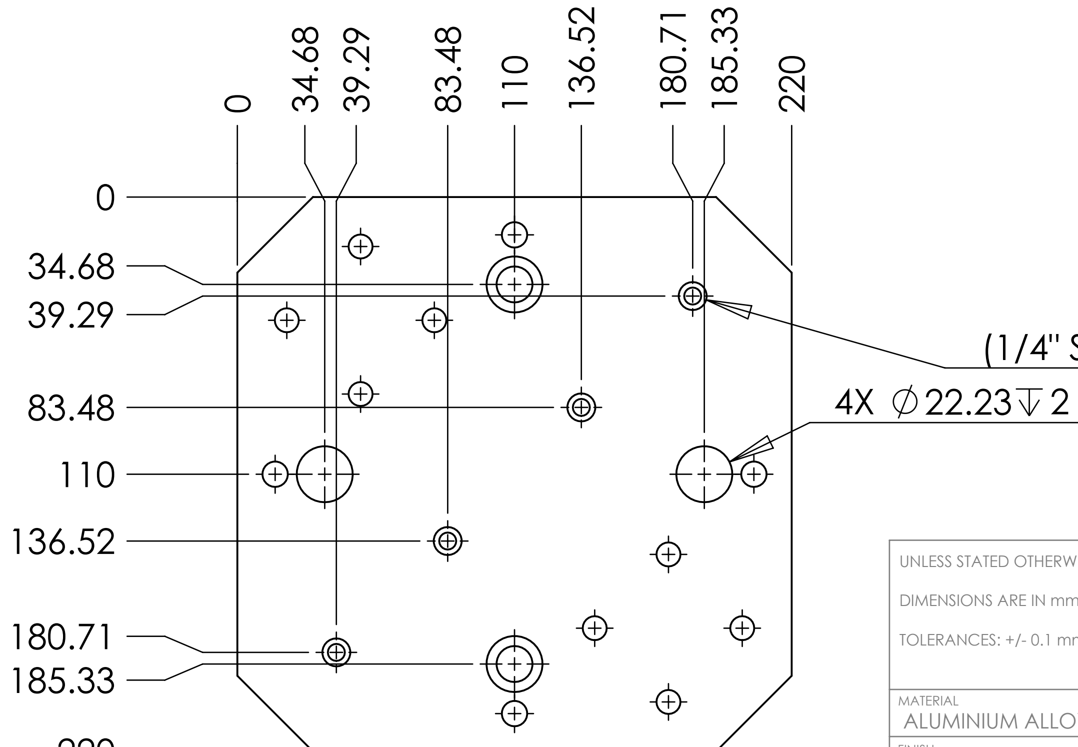




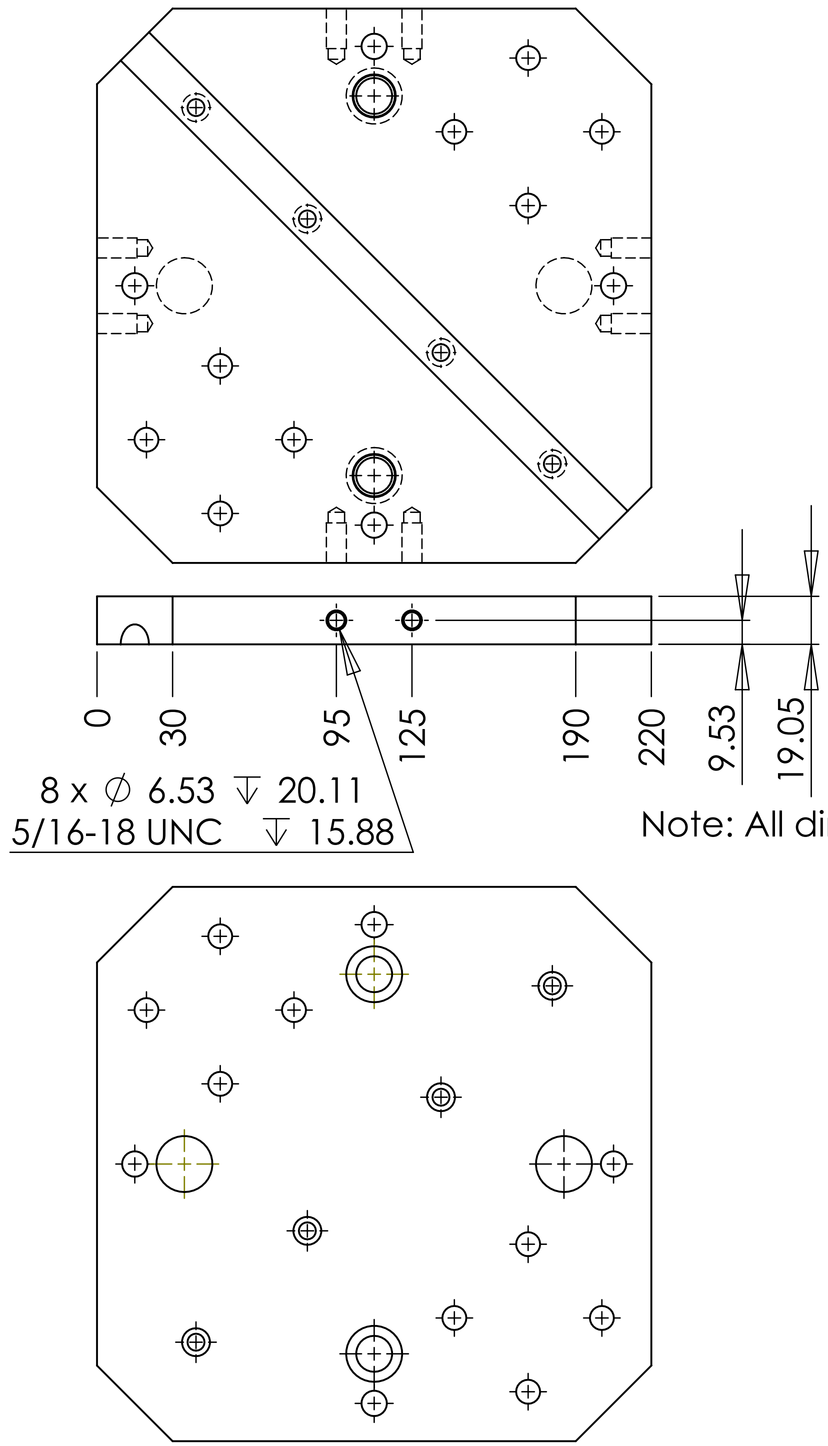


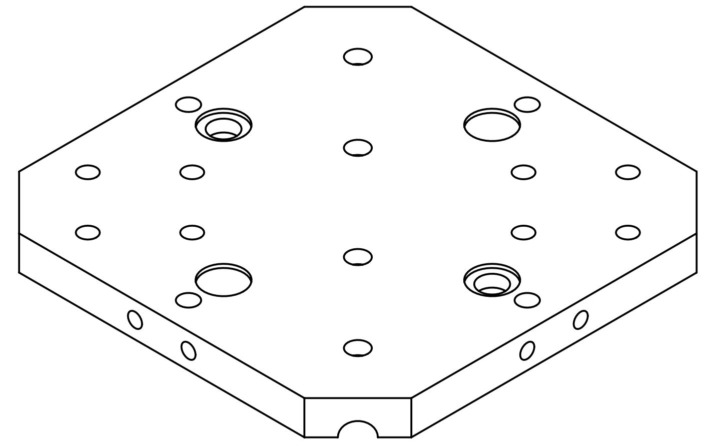
Notes:
1. Top and bottom surfaces need to be skinned so that they are flat and smooth in order to prevent oil leaks.

2. May need to convert from mm to in. to get drill bit size.



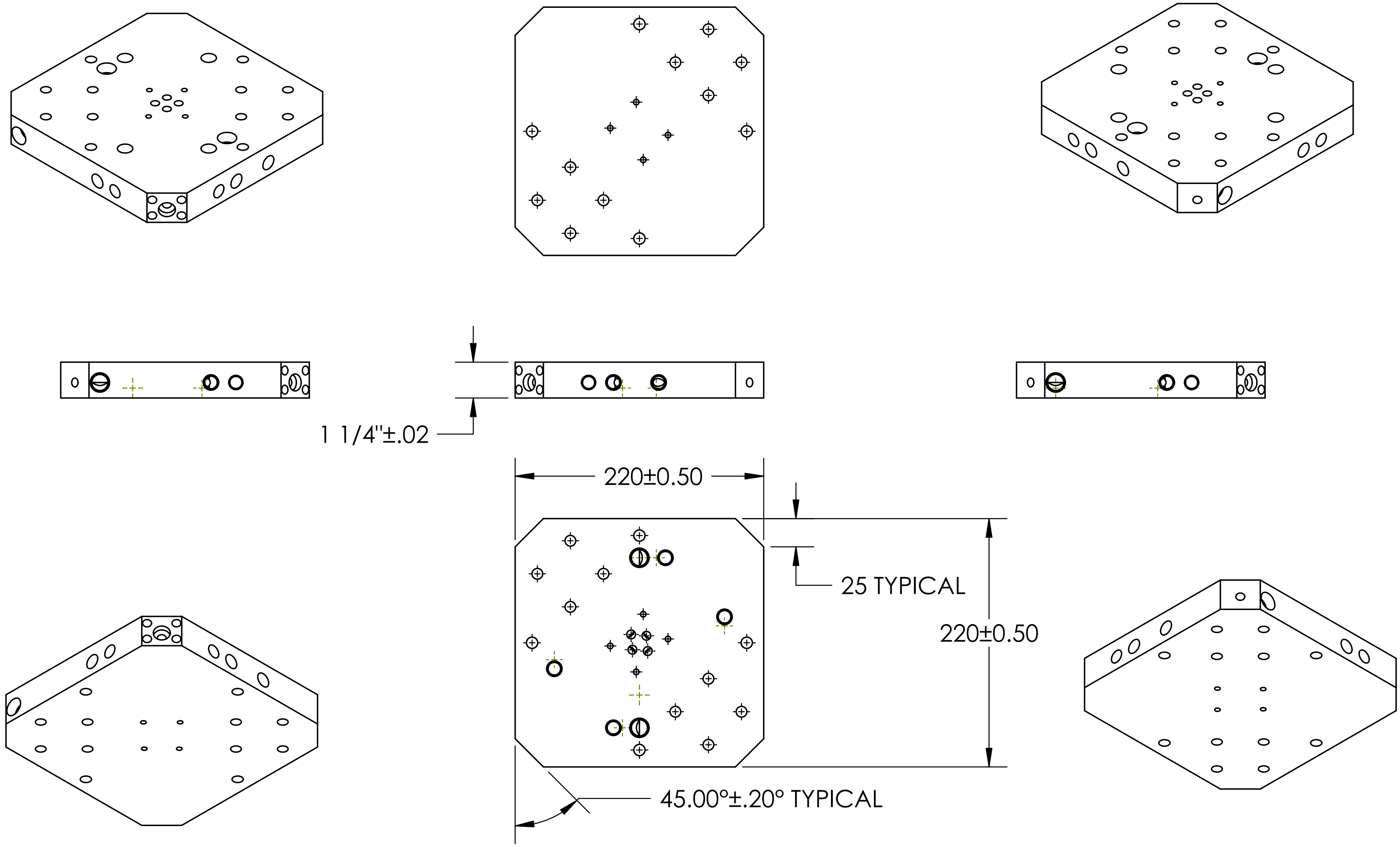
UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/13/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Top Plate (Top View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			SIZE A · DWG. NO. 9 · REV. 2
				SCALE 1:3 · WEIGHT: · SHEET 3 OF 4





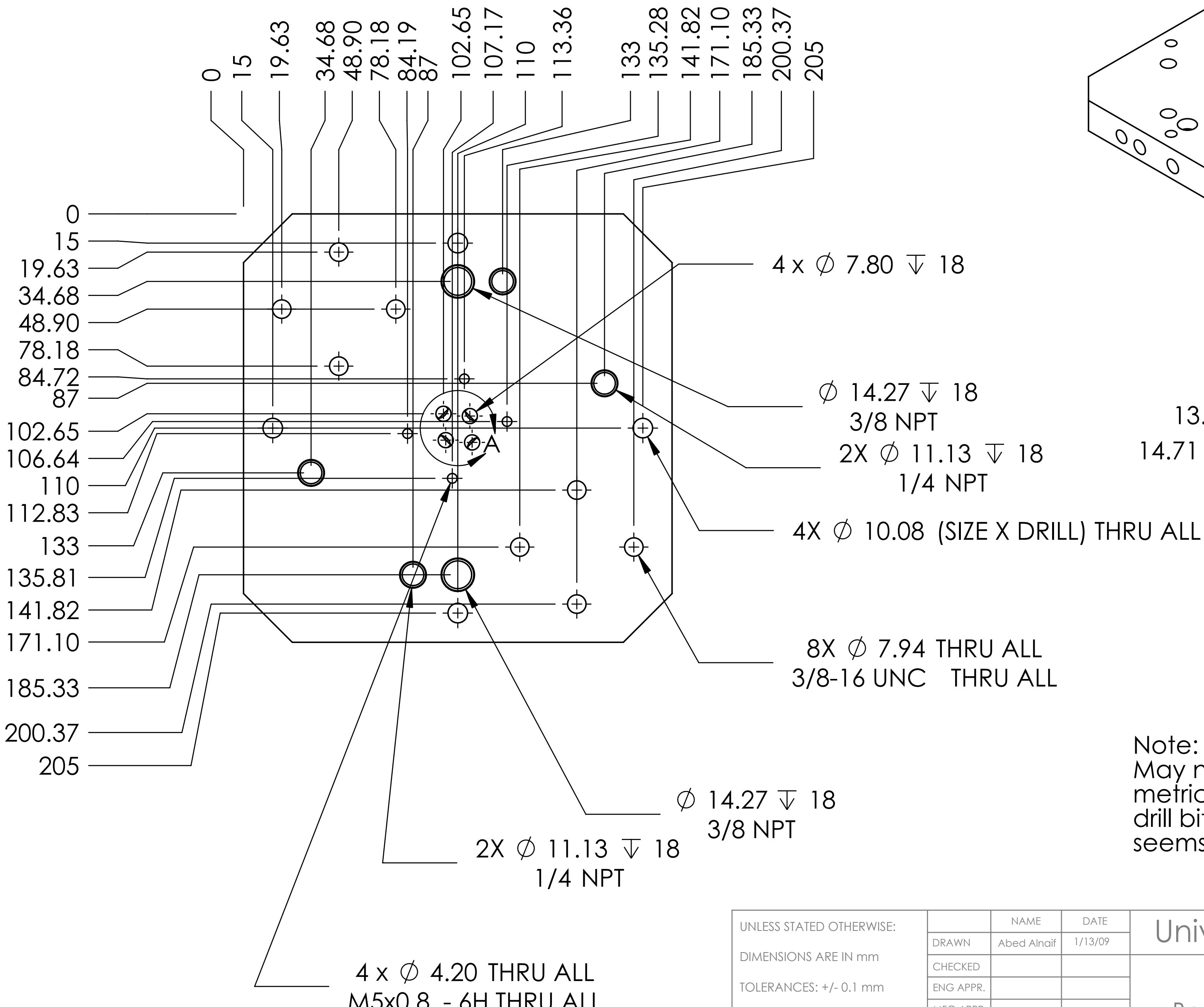
Note: All dimensions typical (for all 4 sides)

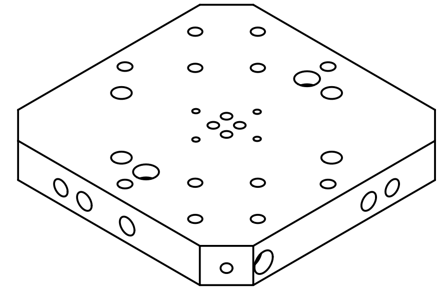
UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/30/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Top Plate (Side View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			SIZE A · DWG. NO. 9 · REV. 2
				SCALE 1:3 · WEIGHT: · SHEET 4 OF 4

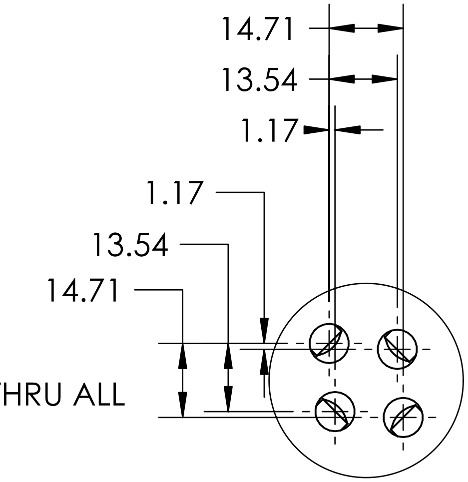


Note:
All surfaces need to be skinned so that they are flat and smooth in order to prevent oil leaks.

		NAME	DATE	
UNLESS STATED OTHERWISE:				University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/13/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Base Plate - 1st Module (Overall Dimensions)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			
				SIZE A · DWG. NO. 10 · REV. 1
				SCALE 1:5 · WEIGHT: · SHEET 1 OF 5





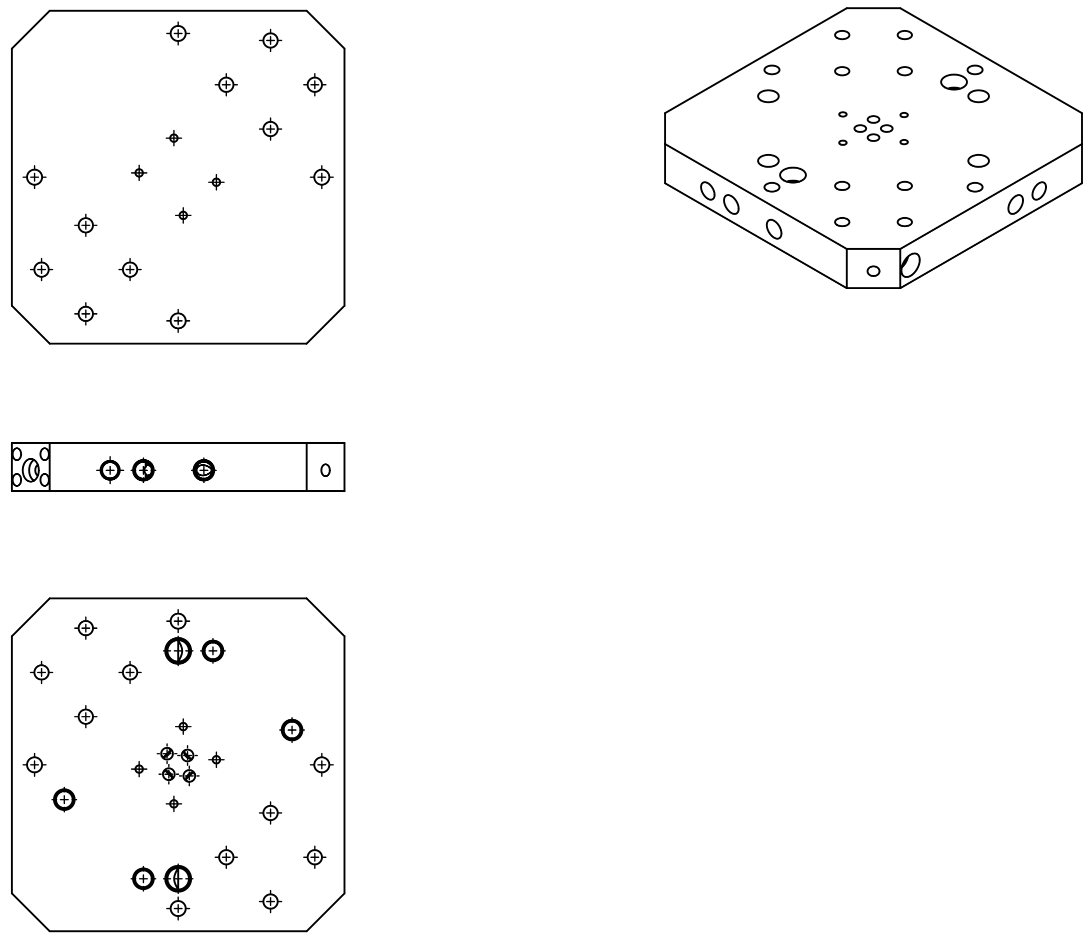


DETAIL A
SCALE 2 : 3

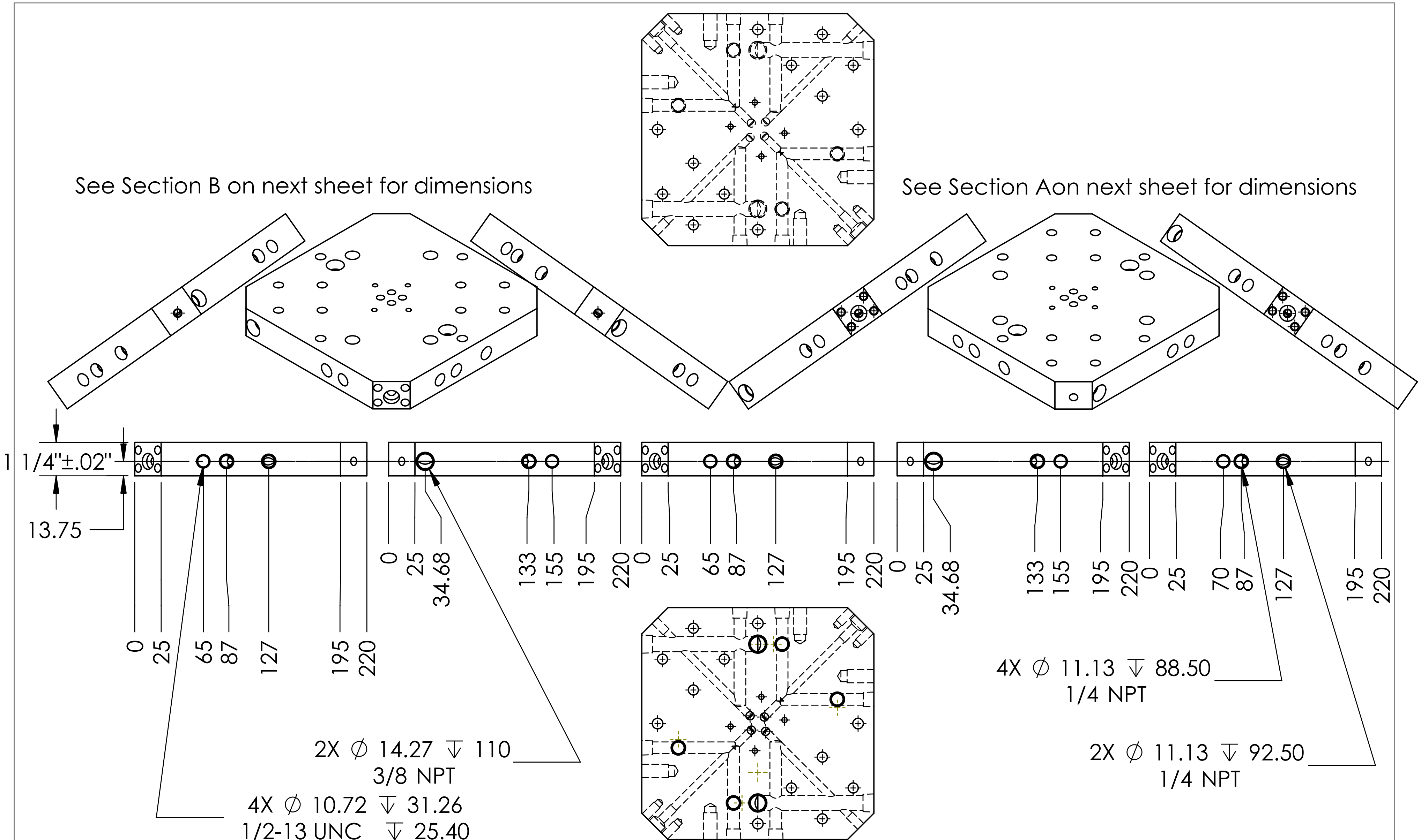
Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)

UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/13/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Base Plate - 1st Module (Top View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. 10 REV. 1
				SCALE 1:3 WEIGHT: SHEET 2 OF 5

Note:
There are no new features to make on the bottom of the plate. This drawing is only included to be consistent with Dwg. # 5.



UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/22/09	
TOLERANCES: +/- 0.1 mm	CHECKED			Base Plate - 1st Module (Bottom View)
	ENG APPR.			
	MFG APPR.			
MATERIAL ALUMINIUM ALLOY 6061	Q.A.			
FINISH	COMMENTS:			SIZE A · DWG. NO. 10 · REV. 1
				SCALE 1:5 · WEIGHT: · SHEET 3 OF 5



Note:
May need to convert from metric to imperial to get drill bit size if the number seems irrational (e.g. 6.91)

UNLESS STATED OTHERWISE:
DIMENSIONS ARE IN mm
TOLERANCES: +/- 0.1 mm

MATERIAL
ALUMINIUM ALLOY 6061
FINISH

	NAME	DATE
DRAWN	Abed Alnaif	1/13/09
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

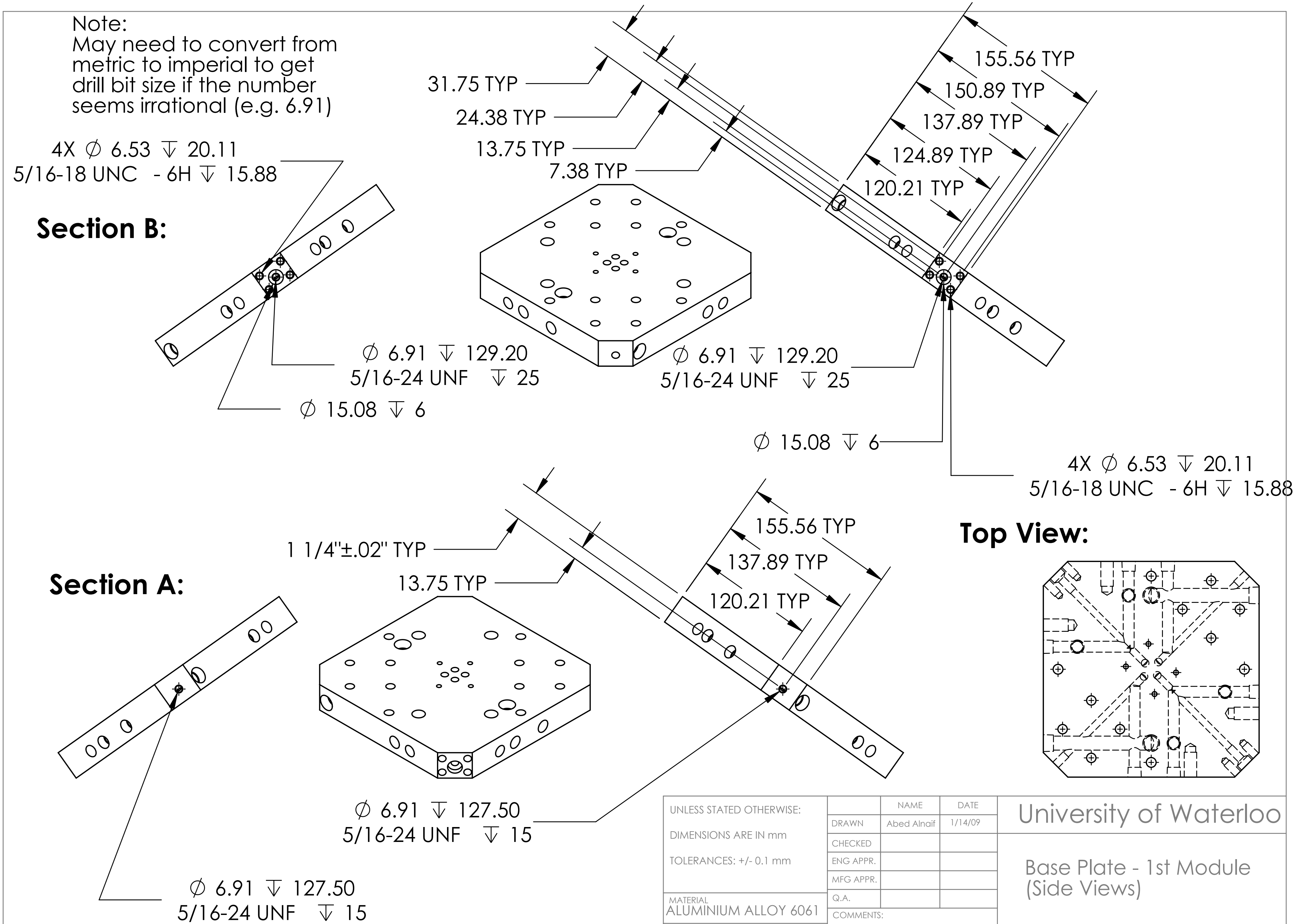
COMMENTS:

University of Waterloo

Base Plate - 1st Module
(Side Views)

SIZE	DWG. NO.	REV.
A	10	1

SCALE 1:5 WEIGHT: SHEET 4 OF 5



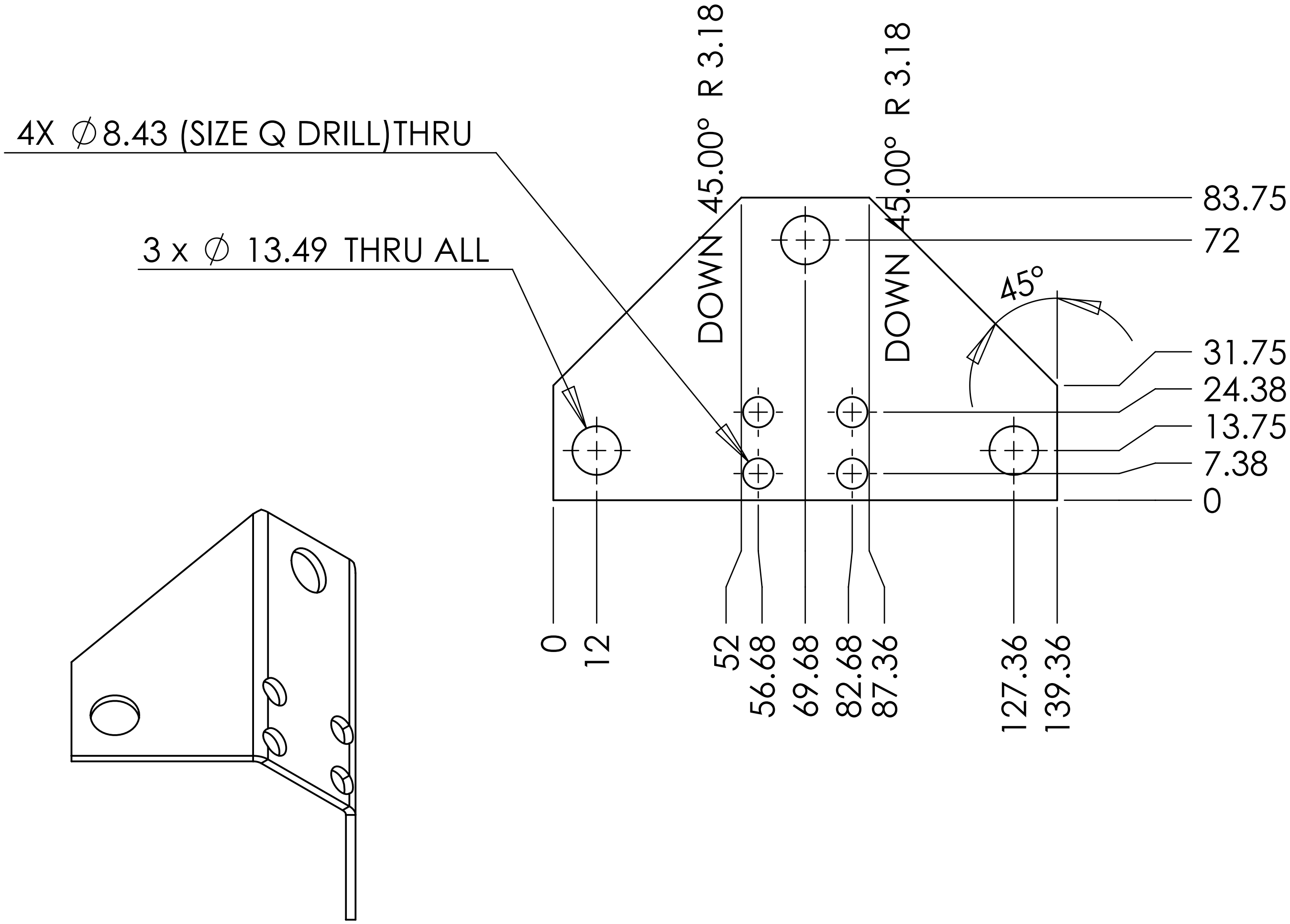
UNLESS STATED OTHERWISE:		NAME	DATE
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/14/09
TOLERANCES: +/- 0.1 mm	CHECKED		
	ENG APPR.		
	MFG APPR.		
MATERIAL ALUMINIUM ALLOY 6061	Q.A.		
FINISH	COMMENTS:		

University of Waterloo

Base Plate - 1st Module
(Side Views)

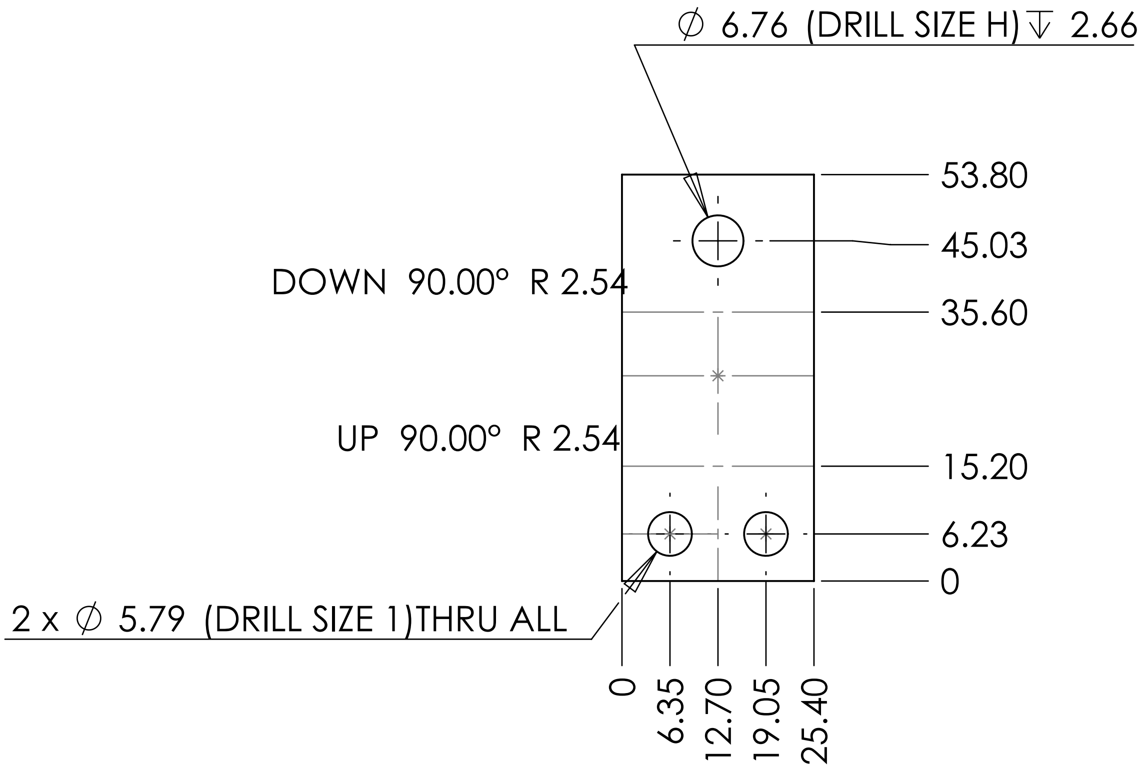
SIZE	DWG. NO.	REV.
A	10	1

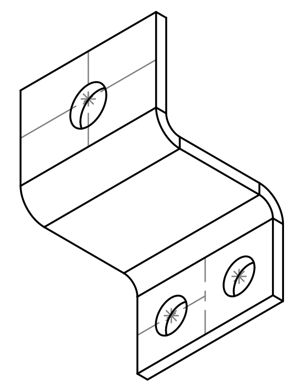
SCALE 1:5 | WEIGHT: | SHEET 5 OF 5



12 Gauge Sheet Metal (Cold Rolled Steel)
Thickness = 0.1046" (2.6568 mm)

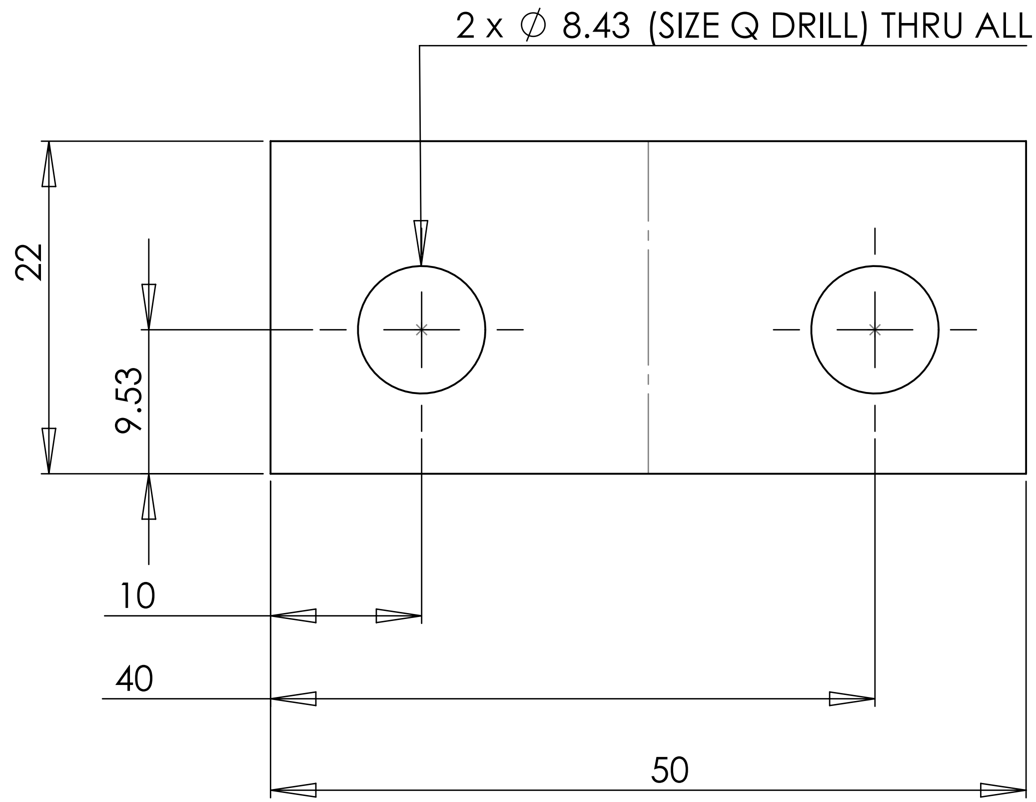
UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/22/09	
TOLERANCES: +/- 0.2 mm	CHECKED			Gusset
	ENG APPR.			
	MFG APPR.			
MATERIAL Cold Rolled Steel	Q.A.			
FINISH	COMMENTS:			SIZE A DWG. NO. 11 REV. 0
				SCALE 1:2 WEIGHT: SHEET 1 OF 1





Note:
14 Gauge Steel Sheet Metal
Thickness = 1.9mm

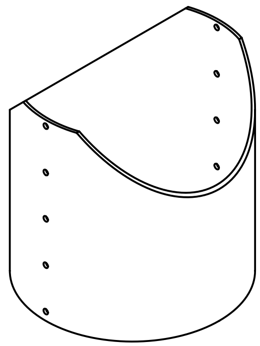
		NAME	DATE	
UNLESS STATED OTHERWISE:				University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/22/09	
TOLERANCES: +/- 0.2 mm	CHECKED			Potentiometer Panel
	ENG APPR.			
	MFG APPR.			
MATERIAL Cold Rolled Steel	Q.A.			
FINISH	COMMENTS:			SIZE A
				DWG. NO. 12
				REV. 0
				SCALE 1:1
				WEIGHT:
				SHEET 1 OF 1

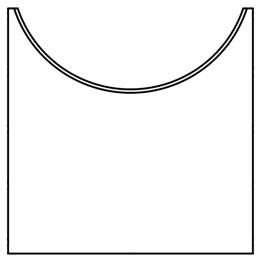


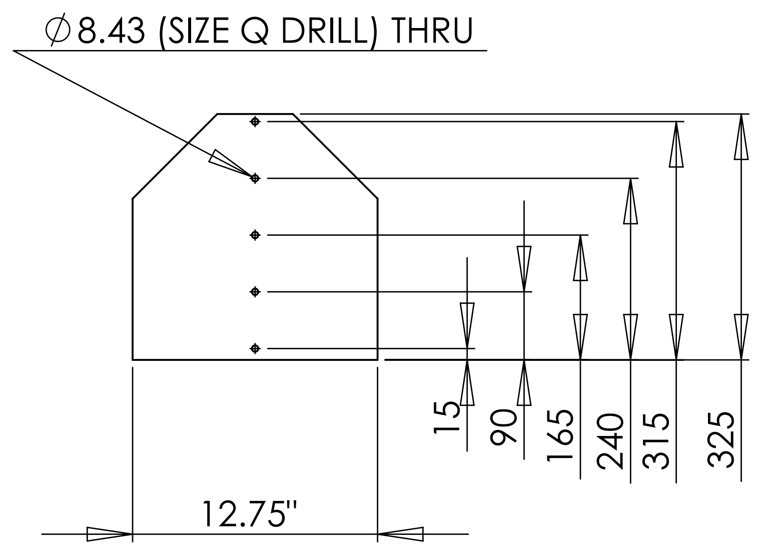
14 Gauge Steel Sheet Metal
Thickness = 1.9mm

UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/25/09	
TOLERANCES: +/- 0.2 mm	CHECKED			Guides
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL Cold Rolled Steel	COMMENTS:			SIZE A DWG. NO. 13 REV. 0
FINISH				SCALE 1:2 WEIGHT: SHEET 1 OF 1

Note: This part was not fabricated for the prototype. This drawing is only included in the report to show design changes.







UNLESS STATED OTHERWISE:		NAME	DATE	University of Waterloo
DIMENSIONS ARE IN mm	DRAWN	Abed Alnaif	1/25/09	
TOLERANCES: +/- 0.2 mm	CHECKED			Cylindrical Housing
	ENG APPR.			
	MFG APPR.			
	Q.A.			
MATERIAL ALUMINIUM ALLOY 6061	COMMENTS:			
FINISH				SIZE A DWG. NO. 14 REV. 0
				SCALE 1:10 WEIGHT: SHEET 1 OF 1