

NASHWHEELS

Final Prototype

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Sponsored by MAX Mobility



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Introduction

MAX Mobility, a company focused on accessibility-centered engineering, presented NASHWHEELS with the task of developing a two-wheel dynamic center of gravity (D-COG) wheelchair designed for individuals with disabilities. In order to achieve this goal without having to develop new D-COG technology, the design will adapt to an existing two-wheel D-COG device (NINO Robotics wheelchair) to make the product more accessible for handicapped persons. In order to achieve the desired results, NASHWHEELS will plan, design, prototype, and validate the new D-COG seating system for employment.

Design Problem and Considerations

Current power chair options for persons with disabilities are expensive, bulky, take up large areas, and are unsafe for the user when operating on inclined surfaces. A two-wheel D-COG wheelchair can address many of these issues, allowing users to remain upright at an incline, using a smaller physical footprint to allow easier access to tighter areas, and employing larger wheels to overcome greater obstacles. However, the few devices available are not sufficiently accessible for individuals with disabilities. This project will focus on adapting a NINO Robotics D-COG wheelchair and address its design limitations: device ingress and egress, method for acceleration, and steering control.

The NINO chair, pictured in Figure 1, has a large handle that impedes the ease of user entry and exit to and from the seat. While the handle is removable, it is not practical for a disabled person to remove the handle, get seated into the chair, pick up the handle, and replace it again independently. Similarly, the handle may prove to be uncomfortable or obstructive for the user's legs during the device's operation.



Figure 1 - NINO Robotics chair with handle inserted on left.¹



Another concern with the NINO Robotics chair is its method for initiating acceleration. D-COG devices accelerate when the center of gravity of the system (including both the device & user) is horizontally displaced from above the center of the wheel (illustrated in Figure 2 by way of leaning). As the COG is displaced, it creates a moment about the wheel. The device then increases its speed to generate a counter moment and keep the user upright at all times. As the distance the user leans increases, the speed of the in-wheel motors increases. While this method of operation may be well suited for fully able-bodied individuals, leaning can prove a difficult and even dangerous task for persons with disabilities.

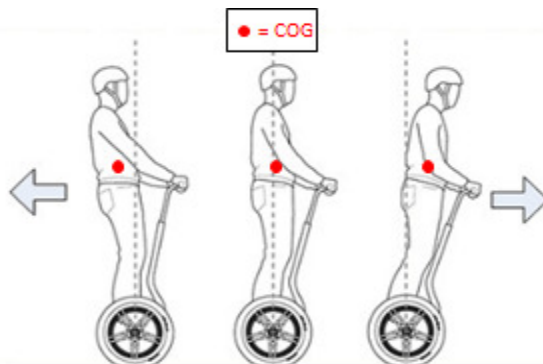


Figure 2 - Acceleration by displacement of COG with respect to wheels.²

In order to remove these limitations and make the NINO device more accessible, MAX Mobility has requested the team to remove the handlebar and design an alternative method for initiating acceleration. Unfortunately, the handlebar also serves as the NINO's method for steering, introducing a new design challenge. Currently, the user tilts the handlebar left and right, creating a torque to rotate the pivot steering control at the base of the device, as seen in Figure 3. This rotation sends a signal to the in-wheel motors and appropriately alters their speed. The final project design must integrate with the onboard electronics to ultimately dictate individual wheel speeds, achieving desired steering control. MAX Mobility has likewise requested all movement – acceleration and steering – to be simplified into one electronic, joystick control. Specific solutions to these design problems are detailed in the Design Solution section of this report.



Figure 3 - Handlebar insert slot for steering control at base of device.



Design Requirements

A number of design requirements must be met as the team adapts the NINO device, with the most important being user safety. Other requirements for the design are listed in Figure 4, and are prioritized for the scope of the project. Top priority items were indicated by the sponsor or determined to be of most important value to the design team. Lower priority requirements were considered throughout the design process, but were of a much lesser importance for design decisions.

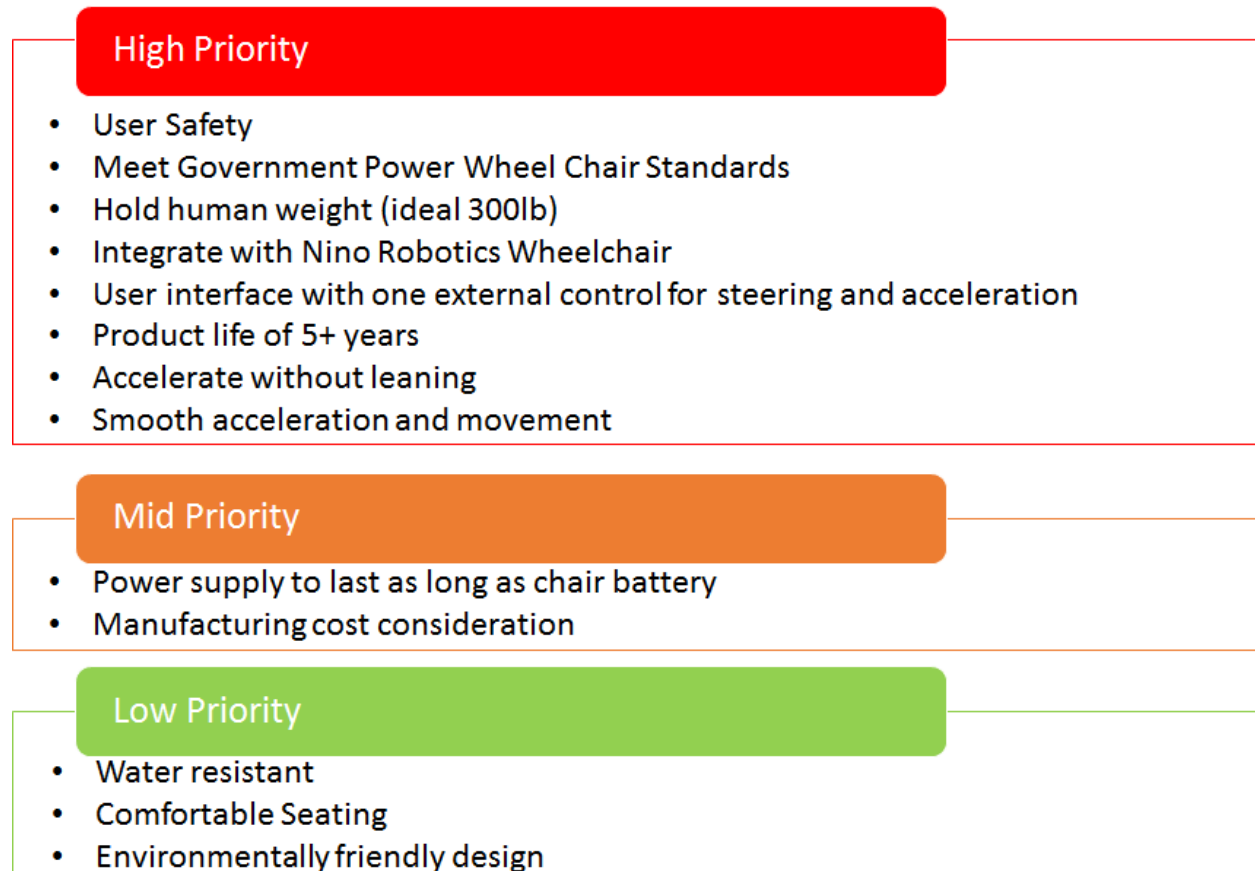


Figure 4 - Design requirements and prioritization.



Design Solution

To meet the challenges set forth by MAX Mobility, the design plan will include removing the steering handle, adding electronic components to control the wheel motors, designing a Mass Displacement System (MDS), and integrating all systems in a single user friendly joystick. With this solution, the accessibility and ease of use of the NINO D-COG chair is improved greatly for disabled individuals.

By removing the handle, users can enter and exit the chair without difficulty. The hassle and impediment of removing and then reattaching the handle with every use is eliminated entirely. With the consequential loss of the primary steering mechanism, an electronic control device, such as a joystick, is to be added as a replacement to provide a means for side-to-side movement. As the user tilts the joystick left or right, a signal will be sent to the chair to rotate itself in accordance with the desired turning action. The joystick will also control the linear acceleration of the device. Tilting the joystick forward or backward will send signals to a newly incorporated motor beneath the seat. As part of the MDS, the motor will be used to slide a mass forwards and backwards to dynamically change the COG of the system without need for leaning by the user. The dynamics of the self-balancing system dictate a mass must be displaced to counteract the moment created by the wheels and prevent the device from simply tipping over. With this constraint, a mass displacement system must be implemented as opposed to strictly altering the NINO's in-wheel motor controls. By designing this additional system to fit within the pre-existing envelope of the vehicle, all size requirements are maintained.

With acceleration controlled directly by the joystick, the need for the user to lean is eliminated. However, if the user were to lean, the device would still accelerate accordingly based on its internal systems. Therefore, a feedback control system will be considered to monitor the wheel speed and adjust the location of COG to match user input from the joystick as desired. This will correct for any additional displacement in COG created by the user, improving the quality of the device.



Further Research into Existing Ninebot Base and Operating System

In order to move forward with many aspects of our design, it became necessary to analyze in detail the on-board circuitry that already exists. Properly investigating these components allowed for greater knowledge about how the base of the chair (a Ninebot Model E) operated. This investigation allowed NASHWHEELS to determine the feasibility of integrating the design with the current electronics in place. This integration was necessary for design plans such as replacing the native steering signal with a NASHWHEELS developed model, investigating motor signals for tracking speed, and utilizing power from the Ninebot battery to power components of the NASHWHEELS system.

Figure 5 below presents an overview of the circuitry found during the team's investigations. One of the first notable aspects of this circuitry are the two large boards that are present (highlighted in blue). The board located on the bottom right of Figure 5 controls the motor that moves the NINO chair, while the board that is centrally located controls the steering and acceleration of the chair. A steering input is received from a bidirectional hall effect sensor located at the base of the steering handle. Further analysis of these boards can be found on the following page with reference to Figures 6 and 7. The next key element in Figure 5 is the four optical foot sensors that exist in the corners of the Ninebot base. These optical sensors are activated when the brakes are lifted, notifying the system that a user is present. At least one optical sensor must be engaged for the base to begin its self-balancing technique. Another key component present is the main power leads from the on-board 60 V battery, which is located on the bottom of Figure 5 and is covered by a white rubber encasement. Finally, the white ribbon that exists on top of Figure 5 allows for a Bluetooth connection from the remote control to the steering board.

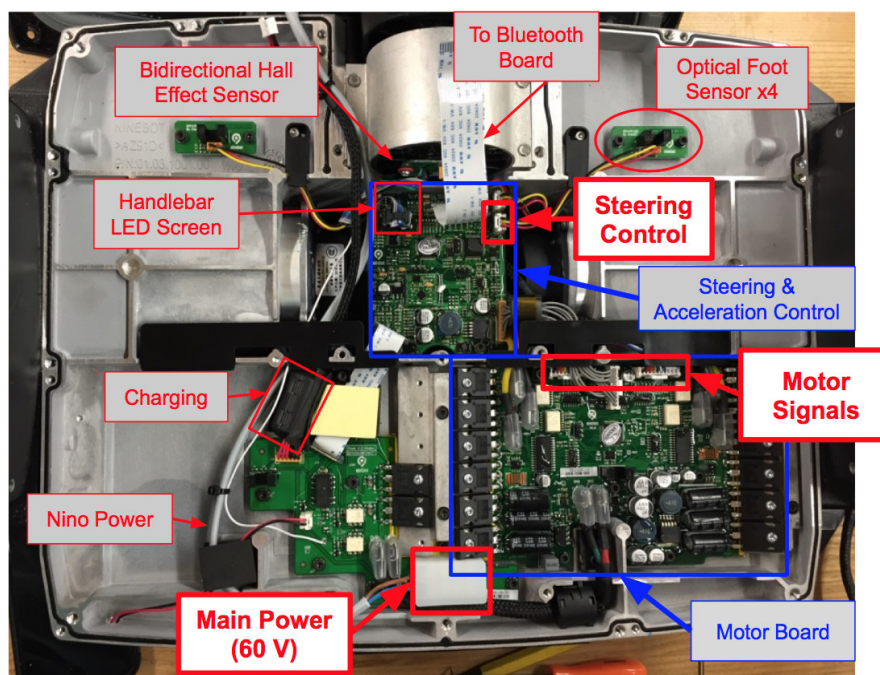


Figure 5 - Overview of circuitry in Ninebot base.



Figure 6 below presents a more in-depth look at the steering board. On the top left are the pins that connect to the LED screen in the top portion of the handle, indicating battery charge and user warning lights. A ribbon located at the top edge of the board connects to the Bluetooth receiver which works in conjunction with the remote and sends real time performance information to a phone app. The integral component of this board is in the three pins that connect at the top right of the figure. This is where the logic behind steering control is implemented and allows for NASHWHEELS to investigate the current design. The Ninebot base controls steering with a bidirectional hall effect sensor located in the base of the handle. As the handle turns and the magnet in the steering handle slot is rotated, the hall effect sensor sends a voltage to the steering board through the connection outlined below. The black wire acts as a ground, the red wire is connected to a 5 Volt source, powering the hall effect sensor system, and the yellow wire is the output voltage from the hall effect sensors, effectively tracking steering. The hall effect sensors input a voltage ranging from 0 to 5 Volts. When the user pulls the handlebar all the way to the left, a voltage of 0 is registered in this yellow wire, and when the user pulls the handlebar all the way to the right, a voltage of 5 is registered in this same yellow wire. The board then uses logic to map this 0-5 range of voltage to turn the device. This is implemented by equally and simultaneously increasing the speed of one wheel and decreasing the speed of the other, based on which way the chair needs to turn.

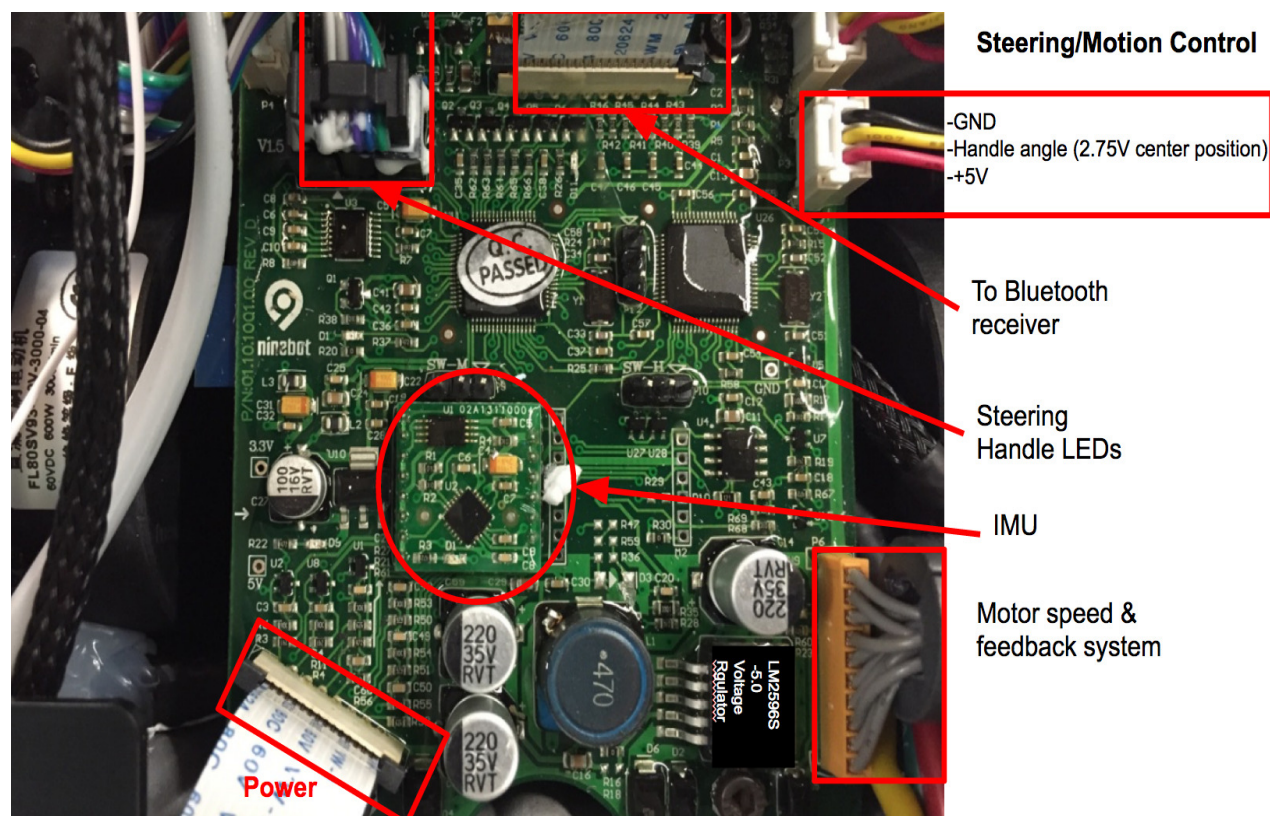


Figure 6 - Steering and motion control circuit.



Figure 7 below analyzes the motor control board in depth. As seen on top, there are hall effect sensors for both the left and right motors respectively. These constantly track the speed of each wheel, allowing the NINO to know how fast the chair is moving and when to appropriately turn on or off the phases of the motor. The power components corresponding to the motor phases are outlined in the figure next to the motor tracking signals. The three phases for brushless DC Motors are distinguished for each side, and the power to this board comes from the power board, seen on the bottom left of Figure 5.

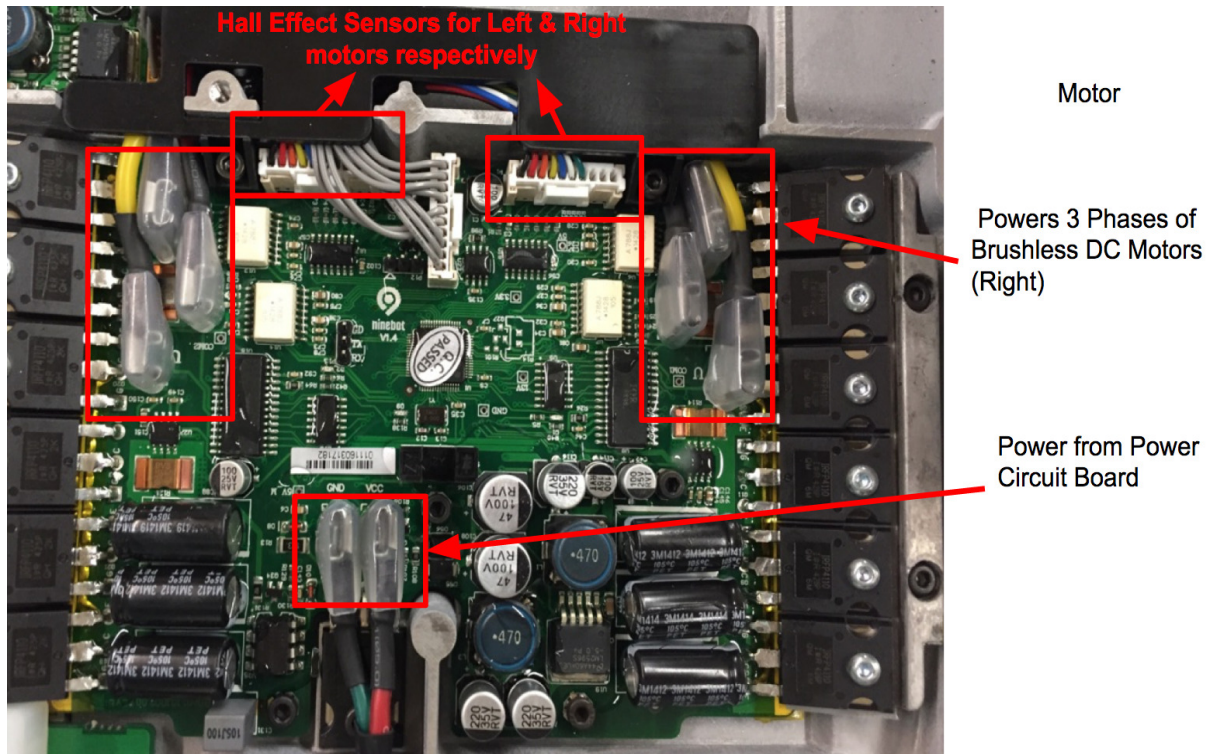


Figure 7 - Motor circuitry.



Design Choices and Justifications

With the overall goal of improving transportation methods for handicapped users, there currently are no perfect devices on the market. While standard and power wheelchairs are the most common solutions for assisting handicapped individuals, they both have their drawbacks. The standard wheelchair requires the user to manually supply the power by rotating the wheels or pushing from behind. Alternatively, the power wheelchair has a large footprint and can be difficult to use in tight spaces. Both of these options can also be dangerous for users when ascending, descending, or turning on sloped terrains. The NINO device incorporated with the NASHWHEELS product aims to be the optimal solution for this problem. The NINO chair is ideal with its small footprint and 0° turning radius. Furthermore, it is easily controlled with powerful motors to assist with quick acceleration and turning for the user. Its inherent self-balancing control system allows for ease of use on inclines. Whereas the alternatives position the user perpendicularly to the terrain, the NINO will keep them vertical at all times, significantly increasing the safety of the user.

It is with these considerations in mind that MAX Mobility has opted to move forward in creating a new system based on the existing NINO model. Because a critical drawback of the NINO device is that the only user input exists through leaning, developing a new system to override this is the cornerstone of the NASHWHEELS design. Figure 8 below illustrates how the movement of COG specifically relates to the NINO chair. When holding a user, the acceleration of the chair is highly dependent on the user's size and weight distribution, and the selected design was developed with this in mind.



Figure 8 - COG and acceleration control of NINO smartchair.



Competing Products

The two-wheel, self-balancing wheel chair market is new to the industry, as engineers are taking advantage of Segway technology and adapting it for users with disabilities. There are very few players currently in this space, creating a business opportunity for companies that are able to create a successful product to meet the needs of this target market. The two largest competitors to NINO (and conversely the NASHWHEELS system) are detailed below.

1) Ogo Technology

The Ogo chair is an advanced prototype created by South American native, Kevin Halsall. By using gyroscopic technology similar to Segway products, the Ogo enables users to control the linear acceleration and steering with the lean of their torsos. The device is primarily designed for individuals with torsal mobility, but the company website states a joystick attachment can be used to control the chair instead of needing to lean, but how this is accomplished remains to be seen. The prototype does not build upon other existing products in the way that NINO builds upon a Segway Ninebot base. Unlike the NINO, the Ogo does not have side armrests, but rather, requires user input through the handles above the wheels. The Ogo is also bulkier than the NINO chair and pricing and performance specification are currently unpublished. Dependent on performance specifications, this product could be NASHWHEELS' largest competitor.³



Figure 9 - Ogo Technology Prototype to begin production in 2017.³



2) Segfree

The other major player in this newly emerging market is Segfree. This product attaches a seating system atop a segway base, similar to NINO robotics. Unlike NINO, however, the design is much less aesthetically pleasing and employs an overall bulkier design. From a functional perspective, the chair operates similarly to the current NINO product with acceleration controlled by leaning and steering controlled by a handle bar. The NASHWHEELS design will have greater functionality for users with disabilities by not requiring the user to lean for acceleration and by occupying a smaller footprint. The cost for this device is \$12.5k.⁴



Figure 10 - The Segfree chair.⁵



The NASHWHEELS Solution

Arriving at the solution to this problem came in two major steps. The first was developing design concepts for the Prototype 1 stage of the project. At this stage of the design process, it was assumed that the position of the user's mass would remain as the input method for the vehicle. The overall design goal was to translate the user's COG by developing a system to electronically reposition the user in their seat. Three different methods of displacing this mass were investigated: a motor-powered two-bar linkage, a motor-powered rack and pinion, and an electric linear actuator. After 3D modeling and building prototypes, the best method of actuation was determined to be the motor-powered rack and pinion design because it allowed for the smoothest, most reliable form of bidirectional linear motion. The major faults of the alternate designs were that for a linkage system, its speed would not be linear, and for the linear actuator, its duty cycle prevented the ability to change directions quickly.

The second major step was revising the input method for the vehicle – instead of repositioning the user, an auxiliary mass was to be used and re-positioned instead, simulating a user's movement. This spurred the design of a self-contained Mass Displacement System (MDS) to be implemented beneath the user. There are no existing products that satisfy this unique design, requiring the team to custom fabricate its own MDS. To design the mass displacement system, the following design choices were made with the corresponding justifications:

Table 1 - Primary design choices and reasoning for MDS development

Design Choice	Reasoning
Auxiliary Mass Displacement system to translate the COG	• Small mass to displace • Lower power motor necessary • Smaller sized motor increases volume available for other components • Better User Experience • User is not jerked to initiate motion of chair • Only motion the user experiences is the movement of the chair, limiting possible motion sickness
Rack & Pinion attached to electric motor to move mass	• Speed of mass can be easily controlled and directly tied to external control device (i.e. joystick) without complicated algorithms • Switching of directions can be instantaneous (no duty cycle obstacles) • Displacement velocity is independent of position (compared to a 2-bar linkage system)
Mass connected between two linear bearings on parallel shafts	• Two areas of contact to dissipate load on structure • Low coefficient of friction between bearings and shafts • Simple assembly • Shaft length can be adjusted to match required length of displacement
Motor attached to same plate as mass	• Required addition mass necessary to meet auxiliary mass requirements is reduced by including the mass of the motor in the system
Manufactured Mass Displacement system housing to be placed in gap between seat and Nino base	• Maintains overall size of vehicle • Length of gap is long enough for necessary mass displacement • Volume of gap is sufficient to hold necessary mass



A model along with a picture of the fabricated Final Prototype design is shown below in Figure 11.

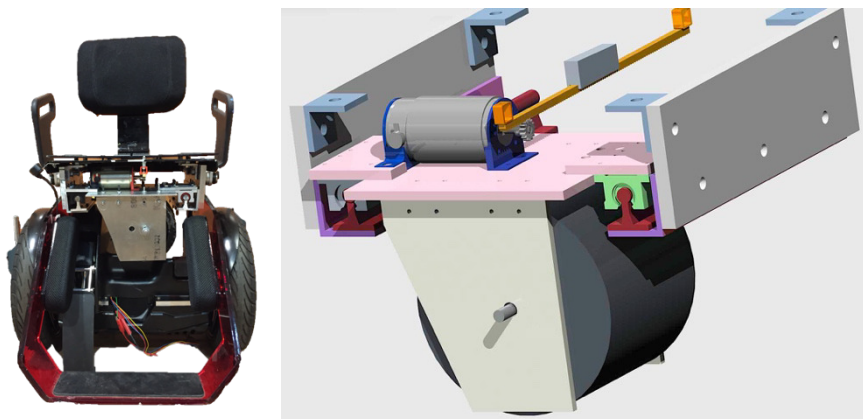


Figure 11 – Final Prototype (left) and fabricated model (right).

The system is attached to the bottom of the NINO seat plate. The shaft housing (gray in Figure 11 on right) is bracketed (light blue) to the NINO in two places, and bracketed (purple) to the shafts (red) along the length of the chair. Linear bearings run along the shafts (two on each side). On the left, the bearings (gray) are fixed alignment, while on the right, the bearings (green) are self-aligning. This combination helps to prevent binding on the shafts. Bolted to the top of the bearings are the plates (pink) that secure the MDS. Below the plate is the mass assembly consisting of the mass housing (beige) through which a pin holds the mass (black). The center of mass is shifted slightly to the right so that the masses fit beneath the chair and can slide without interfering with the NINO brake/electronics housing (seen in Figure 11 on left). Above the plate, the motor is attached with two custom designed 3D printed brackets (blue). The pinion meshes with the rack above it (yellow) which is bolted to the NINO seat plate in three different spots with 3D printed spacers (orange, gray, orange).

The seat in its natural position is not parallel to the ground (the front is angled up at approximately 3 degrees), so washers were added at the front of the shaft housing as well as at the front of the rack to ensure the system slides horizontally. A close-up view of the MDS Assembly is provided below in Figure 12.



Figure 12 - Sliding components of MDS.



All components were designed to fit and move within this small volume, maximizing the existing unused space of the vehicle.

The design choices to determine the mass, displacement, and power required were determined using the results found in the Testing and Analysis section, knowing that:

1. The moment caused by the displacement of the mass would need to be large enough to accelerate the vehicle to its maximum velocity.
2. The mass would have to be displaced at a speed high enough so that the chair could accelerate similar to the rate at which it accelerates due to leaning.

The NINO device by itself currently has a maximum speed of 13 km/hr or 8 mph. After discussion with MAX Mobility, it was determined that the system would not need to achieve the same speed, but that a speed of approximately 5 mph would be satisfactory for this project. Based on this, it was also determined that a moment of approximately 94.6 in-lbs would be required to achieve the desired velocity. To accomplish this with sufficient acceleration, the mass needs to induce a moment at a minimum rate of approximately 94.6 in-lbs/s.

The linear bearings used are lined with self-coating Frelon sleeves. The Frelon rubs off into the rough microsurface of the shaft, filling it and creating a smooth contact surface between the two components. The coefficient of friction for Frelon-Frelon surfaces is typically between .10 and .20. Knowing that for a mass of 34 lbs. the frictional force on the bearings would be about 6 lbs, a calculation was done to determine the ideal motor. With these factors in mind, the smallest electric motor possible was chosen that would be able to operate above 750 rpm at a torque of 105 in-oz. The motor selected operates with a starting torque of 159 in-oz and has a maximum speed of 3456 rpm.

With a gearhead of diameter 0.675 in, the maximum output force of the motor is approximately 29.4 lbs. Hypothetically, with the coefficient of friction as found above at 0.15, this would mean the motor could displace a mass of 196 lbs. That however corresponds with 0 rpm. If our mass needed to move 6 in/s, this would correspond to an rpm of 1675. Assuming a linear power curve between torque and rpm, this rpm corresponds to a maximum output torque from the motor of 81.2 in-oz. This means the motor could drive a force of 15 lbs, which with a coefficient of friction of 0.2, means that our mass could weigh up to 75 lbs. Because these calculations assume a slow speed and a high coefficient of friction, they represent a worst-case scenario. A safety factor of 2 was included, meaning that for all testing, a mass of no more than 37.5 lbs would be used. Hypothetically, with this mass, the motor should be able to push it at a high enough speed to satisfy the requirements. The current design has implemented a mass of 34 lbs.

With this selected weight, to achieve the acceleration requirement of inducing a moment of 94.6 in-lbs/s, the design must be able to move the mass at a minimum of 2.78 in/s.

The other design choices included minimizing the space required for the system. The



MDS needed to be designed to fit within the empty spaces beneath the chair, and the electronics and power supply needed to be compact enough to be housed out of the way of the user. Because extra space on the chair is minimal, it was decided that these components would be placed internally - the power supply would be placed with the NINO circuitry, and the electronics would be placed in the NINO brake housing. The electronics also required a housing so as not to damage any sensitive parts during use. A box was developed and 3D printed that securely held the PCB, associated circuitry, Arduino, and Arduino battery while minimizing volume.

Steering was the other major component of the design process, as removing the large steering handle to increase user accessibility also removed the method for steering the device. During investigation of the NINO chair, the NASHWHEELS team took apart the actual steering handle to find out how the inner workings operated. It was determined that when the user rotates the handle, an internal magnet is rotated about a hall effect sensor. This sensor measures the changing magnitude of the magnetic field, which the chair then interprets as a voltage. This voltage is then calibrated to output a steering speed based on how far the handle is turned.

The NASHWHEELS solution for steering uses the NINO's original magnet and hall effect sensor steering system. A servo motor is attached to the magnet described previously, turning the magnet based on a joystick input. The motor is calibrated to properly replicate the native steering process, allowing the steering handle to be removed.

Finally, limit switches were implemented on both ends of the MDS track, in order to tell the device when the MDS has reached its maximum allowable positions along the track. Hard stops were also implemented as a safety measure in case of a malfunction of these limit switches.

The primary focus of Prototype 4 was on improving the reliability of the electronically controlled mass displacement system and combining this with the steering. The Final Prototype increased reliability of all aspects of the design, finalized steering plans, and implemented limit switches and hard stops. Figure 13 on the following page shows the design progress since the completion of Prototype 3.



Design Component	Proto 3 Completion Status	Proto 4 Completion Status	Final Prototype Completion Status
Auxiliary Mass Displacement System	Complete	Complete	Complete
Auxiliary Mass Housing	Complete	Complete	Complete
Auxiliary Mass Calibration	In Progress	Complete	Complete
Steering Control	To Be Addressed	In Progress	Complete
Electronics Housing	To Be Addressed	In Progress	Complete
Power Supply Housing	To Be Addressed	Complete	Complete
Integrated Control System	In Progress	In Progress	Complete

Figure 13 - Status of design components.



Improvements

Over the course of the year, the NASHWHEELS design team has continued to improve its method for controlling the linear speed and steering of the NINO chair. The Final Prototype improves upon the rack and pinion design concept from Prototype 1, utilizes data from Prototype 2 to create the first mass displacement prototype, and further develops the working, yet inconsistent systems of Prototype 3 and 4. Figure 14 below illustrates each of the first three iterations of the design, and describes their size relative to each other.

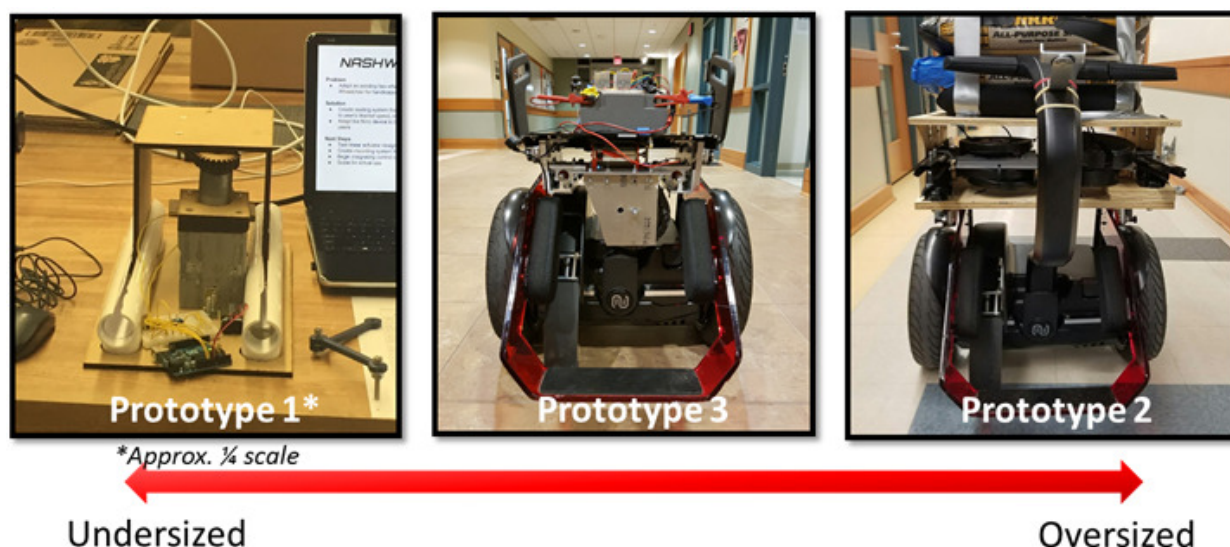


Figure 14 - Relative size of first three prototypes.

The Final Prototype exhibits improvements in five key areas over Prototypes 3 and 4: the mass displacement system, steering control, circuitry joystick controls, power, and feedback control:

Mass Displacement System

A key issue that existed with Prototype 3 was inconsistent motion of the Mass Displacement System (MDS). The system would move backwards easier than forwards, and would encounter significant frictional and torsional forces as it moved, resulting in an inability to consistently operate. The main reasoning for this problem was due to the center of mass of the MDS not being directly underneath the axis of power transmission from the motor. In order to overcome this in Prototype 4, adjustments to the MDS needed to be made. First, the rack was realigned to a more central portion to be aligned with the center of mass and eliminate the undesired torsional force. This required an adjustment of where the 3-D printed brackets existed to slide the entire motor along the plate. The realignment can be seen in Figure 15 on the following page. The MDS from Prototype 3 is on the left, and the realigned system for Prototype 4 can be seen on the right.

Next, the bearing setup was improved. In Prototype 3, one self-aligning bearing was



used on each railing (each side). The design team realized that proper alignment calls for a fixed bearing on one side, and a self-aligning bearing on the other. Additionally, it was determined that using a double bearing setup on each side will aide in decreasing the torque experienced. With this in mind, Prototype 4 combines both of these ideas, implementing a double fixed bearing on one railing, and a double self-aligning bearing on the other.

Additionally, the motor output force was increased by decreasing the gearhead size. The smaller gear size also improved the frictional torque on the motor shaft caused by the gear's set screw. Further, and most importantly, the gear could more easily overcome the resistance experienced on the rack, allowing the MDS to operate smoothly and with less resistance. As seen in Figure 15 below, Prototype 3's gear on the left is significantly larger than that of Prototype 4 on the right.

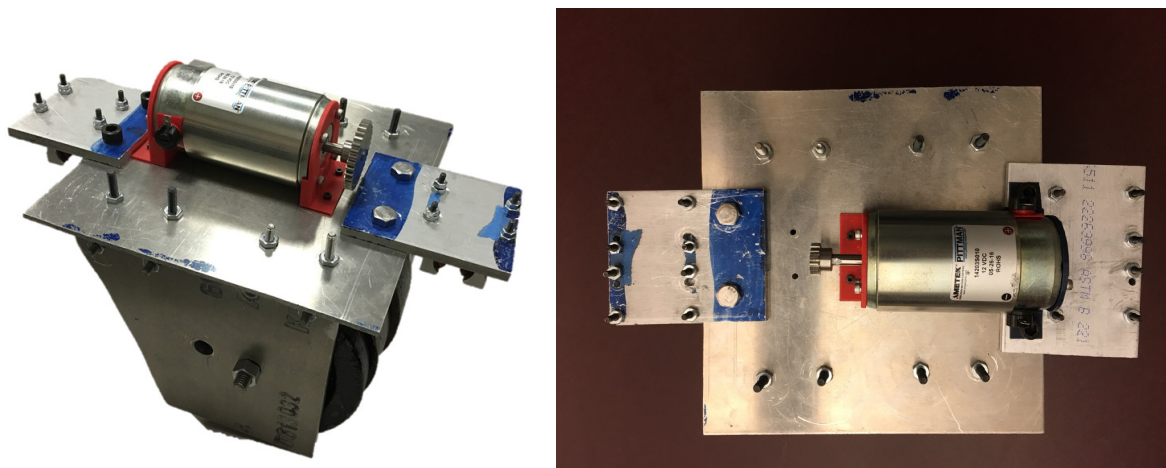


Figure 15 – MDS progress from Prototype 3 (left) to Prototype 4 (right).

Another issue experienced with the previous MDS was pinion slipping on the rack. As a result, the MDS did not move in a smooth motion. This was overcome in Prototype 4 by utilizing 3D printed spacers above the rack to lower it, and additionally stabilize it along its entire length.

Steering Control

After initial analysis of the NINO chair and the circuitry inside the Ninebot base, it was determined that the best method to replace steering was to simply replace the signal from the native steering control system. The idea was that this would allow for the most consistent steering control in our design. After a plan was put together to implement this for Prototype 4, it was found that the chair expected an AC signal for steering, and NASHWHEELS was providing a DC signal, which ruined circuitry and didn't allow for consistent control. It was at this point that the steering handle was cracked open, and the hall effect sensor was found. A new method was then put into place to control steering for the Final Prototype.

NASHWHEELS took the device's current dual-magnet and attached it to a servo motor. This motor has the capability of turning the magnet with respect to the device's internal hall



effect sensor. An Arduino is used to control the actual motor, and trial and error was used to hard code the servo motor (with magnet attached) to replicate steering in its natural form. A key component to this calibration step was knowledge of how the Segway base interpreted the magnetic field from the hall effect sensor. When the steering handle is pulled all the way to the left, the hall effect sensor registers a magnetic field, which is converted to a voltage of 0 Volts. Conversely, when the steering handle is pulled all the way to the right, the sensor registers a different magnetic field, which is converted to a voltage of 5 Volts. It was determined through testing that the safe range of voltage that NASHWHEELS wanted to use as limits was 2.3 Volts and 3.1 Volts, with a centering value of 2.7 Volts. By using a multimeter to read outputted voltage, the pulse width with respect to a given duty cycle for the servo motor was modified iteratively using Arduino code, until the motor properly modeled native steering.

By modifying the magnetic field around the hall effect sensor via the servo motor, the presented design maps movement from left to right on a joystick to left to right in the chair, as is discussed in the following section. By integrating our control system into the existing circuitry, the wheels still operate in the same method, where a voltage of 0 V corresponds to moving left at the vehicle's maximum rotational speed, and a voltage of 5 V corresponds to moving right at the vehicle's maximum rotational speed. Voltages in between those values are mapped accordingly. The way steering is physically implemented involves changing each individual wheel speed as was discussed in the Further Research into Existing Ninebot Base and Operating System section. Because 0 Volts and 5 Volts correspond to dangerously high rotational speeds for the user, the joystick was limited at inputting voltages from 2.3 V to 3.1 V, as described above. At these maximum values, the wheels would increase or decrease in speed by .5 mph to turn the vehicle.

The servo motor with magnet attached is housed in 3-D printed parts that were custom made to replace where the handle bar used to attach. This can be seen below in Figure 16.

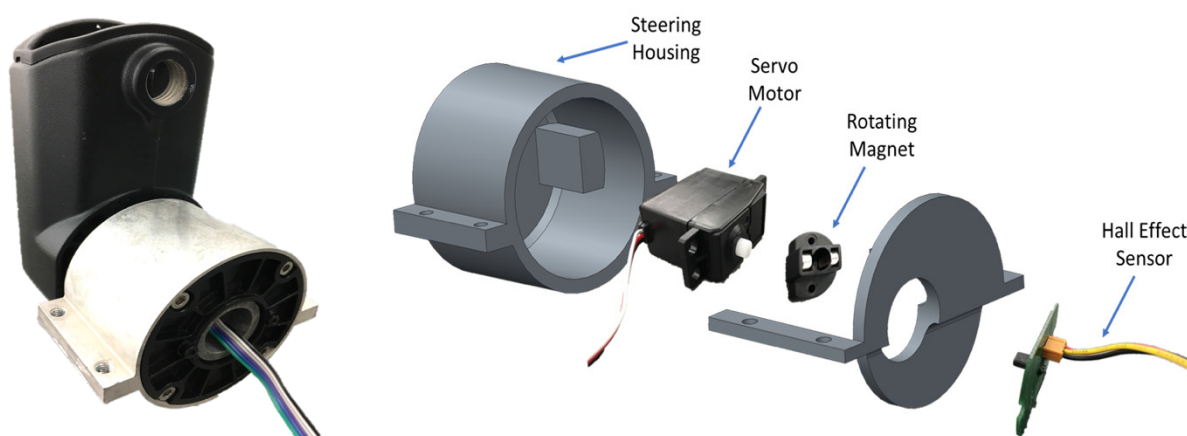


Figure 16 – Old steering housing (left) and new steering components (right).



Circuitry and Joystick Controls

In Prototype 3, a joystick was added to control the Mass Displacement System. The design has since progressed, integrating MDS control and steering to allow for a single user input to control both axes of motion of the chair.

MDS Control

The joystick's forward and aft movement along the x-axis relates to the speed and direction of the MDS movement. This signal from the joystick is sent to the Arduino processor, where it is then mapped to an appropriate PWM signal value for the MDS motor. An H-bridge using high capacity MOSFETS delivers the power from a separate 12V source (based on the PWM signal) to the MDS motor. With the joystick's analog output, the user is able to increase the speed of the MDS by pushing the joystick to a greater degree. It is possible to achieve a range of speeds for the MDS motor from the analog output of the joystick, but qualitative testing of Prototype 4 has shown it is intuitive for the user to simply move the joystick to its extreme and move the MDS at maximum speed until the desired acceleration is achieved.

Steering Control

As explained previously, the steering control for the Final Prototype operates by translating a signal from the left and right movement of the joystick along its y-axis to a voltage that is sent to the servo motor, which rotates the dual-magnet about the chair's internal hall effect sensors via Arduino. Circuitry within the NINO chair translates the signal from the hall effect sensors into a steering signal that is sent to the in-wheel motors.

Circuitry

All controls via joystick are integrated in a single circuit. A schematic of the circuit can be seen in Figure 19 below, while a wiring diagram can be seen in Figure 20. In addition to combining steering and MDS controls into the joystick input, the circuit construction was improved by creating a printed circuit board. The new PCB is shown in Figure 18. With the PCB, the circuit is more compact and the connections between components are more reliable.

Electronics Housing

The circuitry design has been vastly simplified and condensed in the Final Prototype. With the new PCB, a housing was designed so that it could fit compactly in the NINO brake housing. The 3D printed housing allows for the PCB, all associated circuitry, the Arduino, and the Arduino battery to all be placed securely together, out of the way of the rest of the system. A picture of the housing can be seen below in Figure 17.

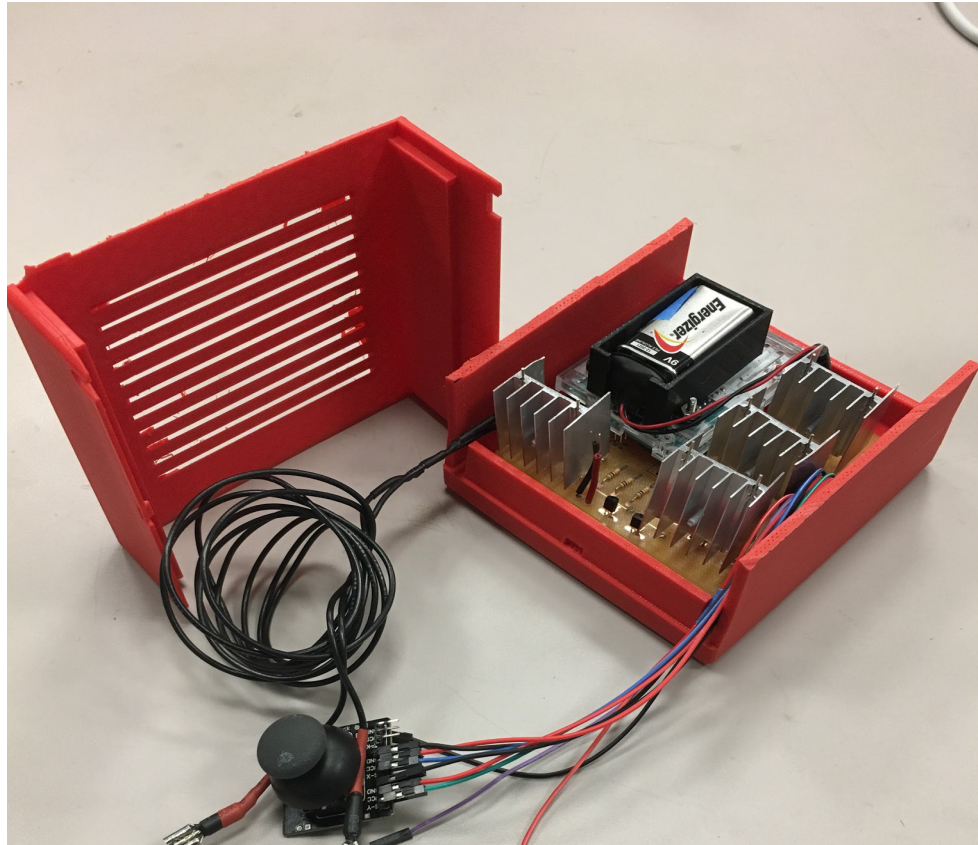


Figure 17 – All circuitry components inside the 3-D printed housing.

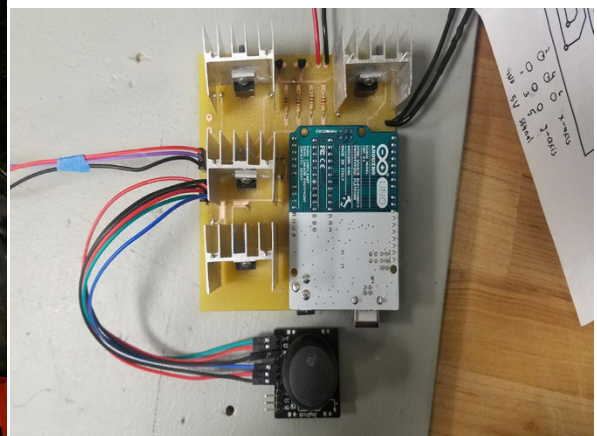
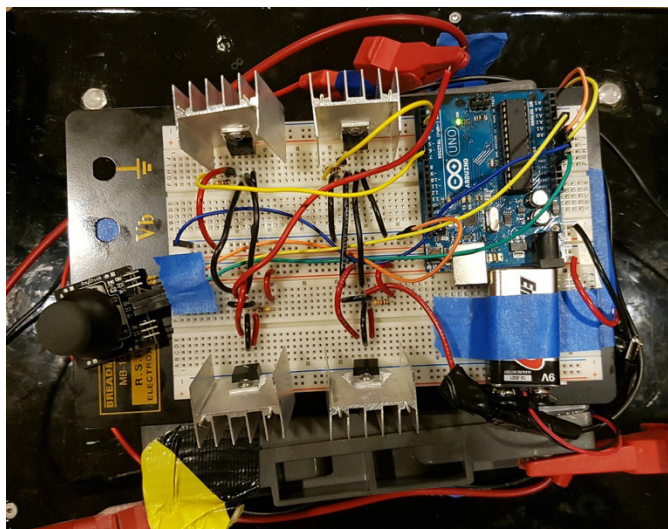


Figure 18 - Circuitry from Prototype 3 (left, breadboard) to Final Prototype (right, printed circuit board).

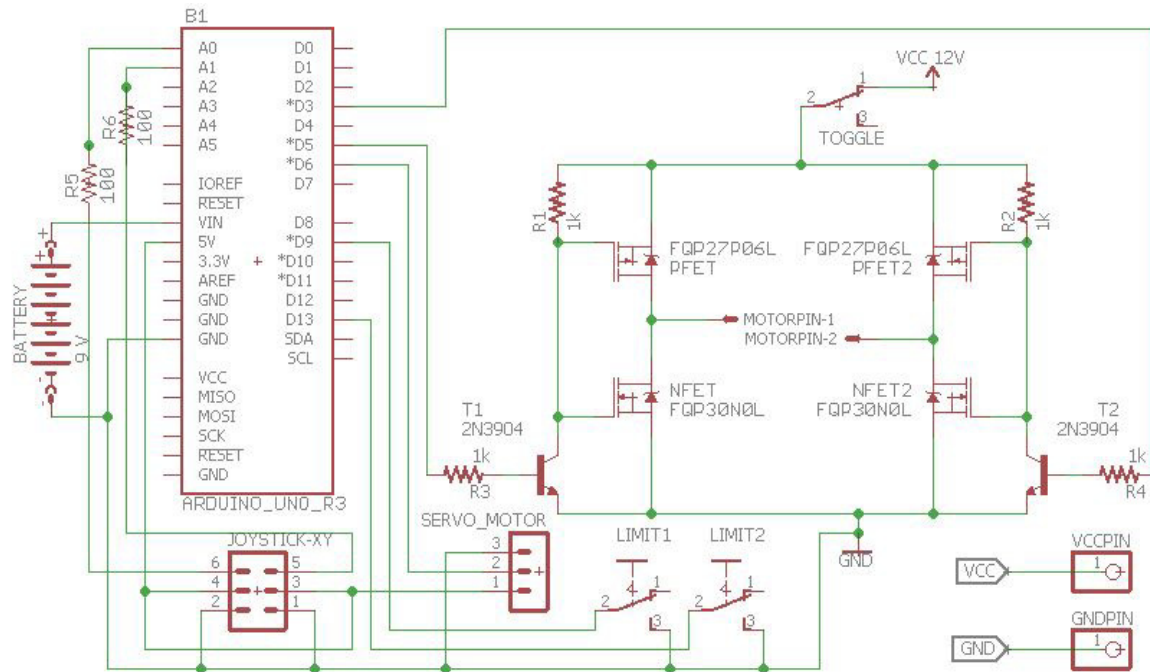


Figure 19 - Schematic of Final Prototype circuitry.

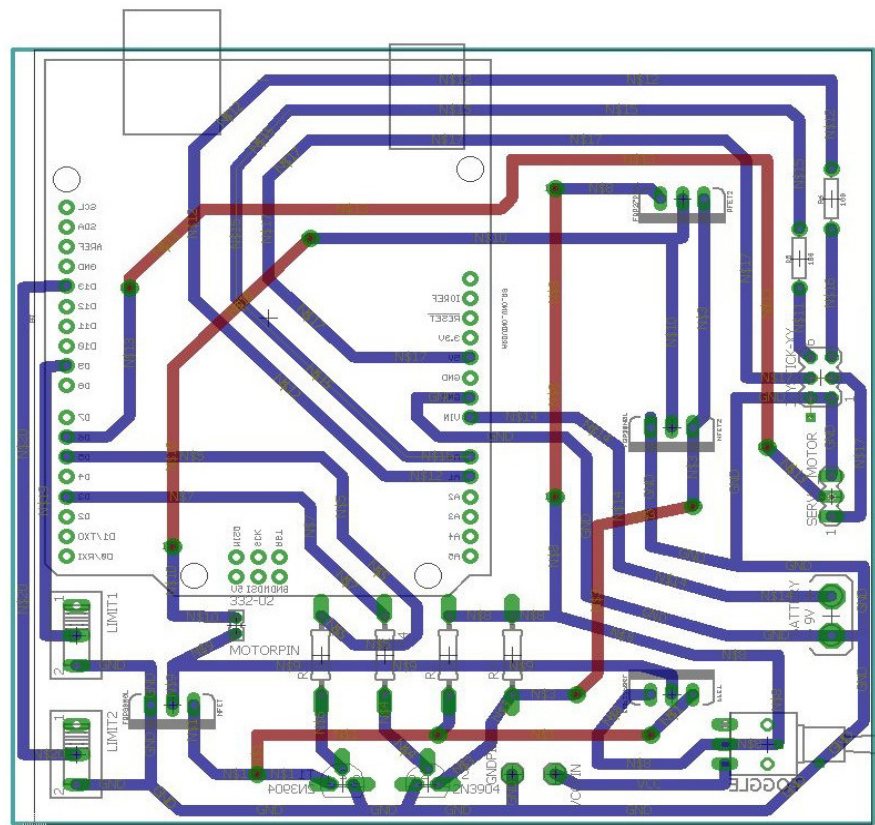


Figure 20 - PCB Wiring Diagram.



Power

Prototype 3 required a number of different power sources: 9V battery for the Arduino, 12V battery to power the MDS motor, and a 60V battery inside of the NINO. To simplify our design and make the design more compact, Prototype 4 and the Final Prototype added a power converter to step down the 60V power available from the NINO battery to a 12V source compatible with the MDS motor. The converter neatly fits into the base of the NINO, as seen in Figure 21 below, completely removing the need for an additional 12V battery and completing the power source housing design requirement.

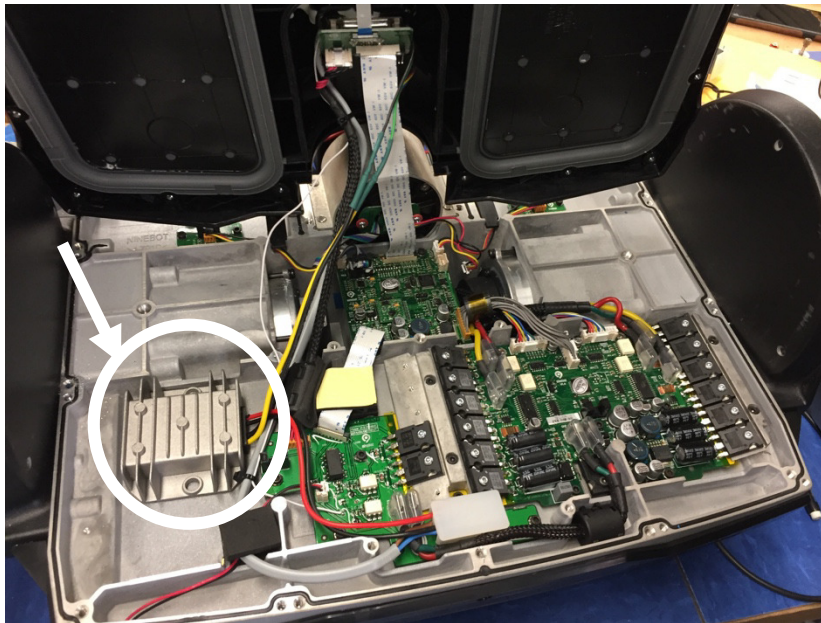


Figure 21 - Step down converter added inside Ninebot base, highlighted in the white circle.

Feedback Control

Feedback control was developed, but with the current state of the device was not feasible for full implementation. The team has started the first step in developing the feedback system by finding the signals from each of the wheel's motors and reading its speed and direction through Arduino. If this option were to be realized, NASHWHEELS would proceed with getting a more powerful microprocessor to store data and combine the feedback control programming with the current steering and MDS control programming. A position sensor such as a linear encoder for the MDS motor gear or a high resolution optical sensor would be needed to dictate the position of the MDS as a part of the feedback control equation. With the speed data sent directly to the microprocessor in real time, the Arduino would then be used to adjust the position of the mass to ensure the user is balanced at all times. The correlations between mass movements and chair accelerations are important in order to calibrate the chair to satisfy the user.



Final Solution

Figure 22 below shows the NASHWHEELS Final Prototype in its entirety, while also noting three of the primary features.

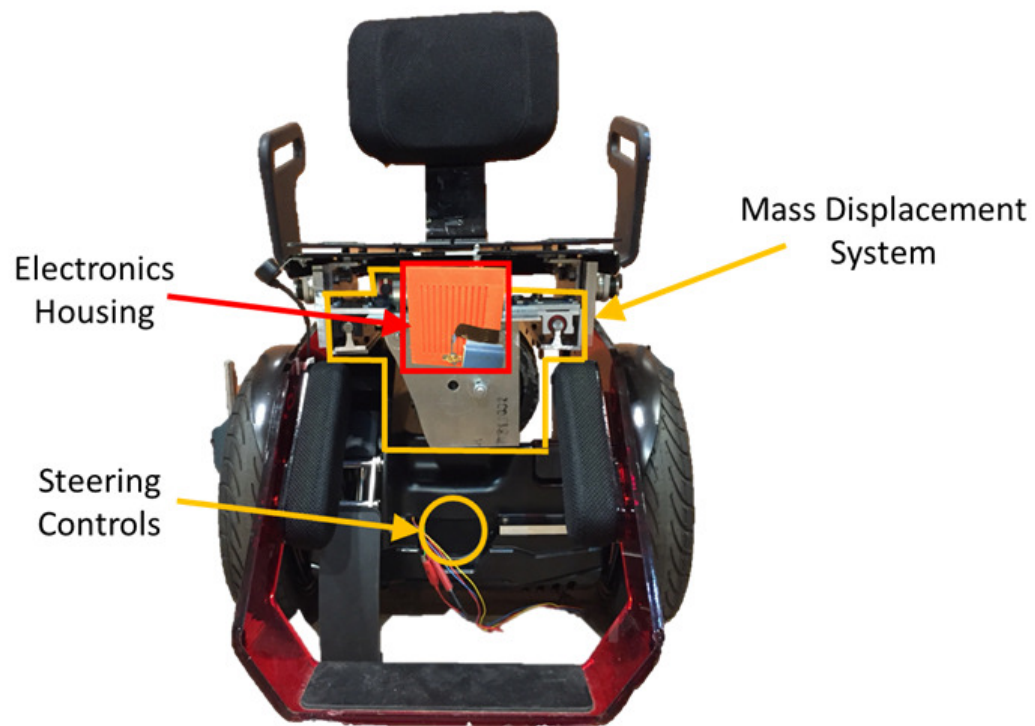


Figure 22 - Final Prototype.



Testing and Analysis

NASHWHEELS has many high priority design requirements that the Final Prototype was designed to meet. As an introduction to the testing that has been done, an overview of many of these requirements is described below. Each section mentions relevant tests that have been considered and/or performed, which are described in depth further in the Testing and Analysis section.

Design Requirements

1. User safety

User safety is of the utmost importance in the development of the NASHWHEELS device. The Final Prototype is the first to work not only as desired with forwards/backwards and lateral movements, but also consistently. As a result, Prototypes 1-4 were all deemed unsafe for a user to ride, but the Final Prototype has progressed to a level where the thought has been entertained. With safety in mind, the NASHWHEELS team wants to further test reliability with masses modeling a user before placing an actual human on the chair.

2. Meet Government Power Wheelchair Standards

For this product to be sold in the U.S. and be eligible for insurance coverage, a number of government standards need to be met. All envelope requirements have been maintained as our device does not increase the overall size of the vehicle in any direction. A key advancement in this area was the newly implemented circuitry housing, which encloses the PCB, Arduino, battery, and all additional electrical components. This eliminated the old, large, and bulky 12V battery that was in use. In addition, all standards met previously by the NINO device have been upheld. With this in mind, no government standards have been violated in the NASHWHEELS design solution.

3. Hold Human Weight

For the product to have a durable life and be reliable for users, it must be capable of handling the weight of a human load not only from a structural standpoint, but with the limitations of the self-balancing system in mind. The testing of this requirement has been completed while the brakes are down, as users of different masses have been seated in the wheelchair without problems. The addition of the auxiliary mass decreased the weight limit of the user for the device to 180 pounds during use, but it can still operate within its designated range.



4. Integrate with NINO Robotics Wheelchair

NASHWHEELS' sponsor, MAX Mobility, requested the design team create a single joystick control to be integrated with the NINO chair to control motion. This requirement has been implemented by adding an auxiliary mass displacement system to the existing cavity beneath the chair that simulates the user leaning forwards and backwards. Additionally, steering control is added via an external servo motor, thus maintaining the integrity of the NINO Robotics wheelchair.

5. User Interface with one external control for steering and acceleration

This requirement is justified as it adds to the user experience by increasing accessibility, allowing for movement in all directions with a singular joystick. Development from Prototype 3 to Prototype 4 was successful in controlling both the MDS system for forward and backward chair acceleration as well as steering using a joystick. The testing on Prototype 3 involved seeing whether or not joystick movement in conjunction with H-bridge control could alternate properly between forwards and backwards movement on the same axis. It was determined that this was a success through repeated functionality testing. The testing of Prototype 4's control interface focused more on combining the steering control into the pre-designed MDS motor control joystick, and designing a more organized control circuit for the whole system, which was finalized on a PCB for the Final Prototype. Testing was done to calibrate the joystick for varying the linear speed of the motor and the rotational speed of the chair. Based on the testing, the joystick was programmed to turn the motor at its maximum speed when the joystick was pushed to its maximum displacement, with the same working principle for the steering control.

6. Product life of 5+ years

This requirement came from the sponsor, Max Mobility. While duration testing would provide results that could verify this requirement, the Final Prototype hasn't been around for more than a week. At this point, the only way that NASHWHEELS can address this requirement is by purchasing parts that list product lives of greater than 5 years, as well as designing the system so that parts (such as the shaft) can be easily replaced when they wear out.

7. Accelerate without leaning

This requirement is the primary reason why we are undertaking this design effort. The goal is to make the NINO Robotics chair more accessible for disabled users, and thus we are aiming to eliminate the need to lean to accelerate. This concept has been tested, but due to safety concerns, the full scale test with a rider on the seat has not been tested yet. When the mass is moved, the chair does in fact accelerate either forwards or backwards depending on the placement of the mass. From previous testing



analysis, NASHWHEELS is confident that the displacement of the mass is sufficient to drive the vehicle while the user is riding and allow them to reach their target speed. The testing has been validated in an empty chair and quantitative results will be available once reliability testing allows for users to be on the chair.

8. Smooth acceleration and movement

Smooth acceleration is necessary for optimizing user experience. The improvements made to the MDS for Prototype 4 resulted in a consistent, smooth sliding motion along the rail. The MDS movement has been tested and confirmed to work consistently within an acceptable speed range at various inclines. Additionally, smooth acceleration has been verified at various user masses (modeled by sand bags), as described in further Testing and Analysis sections. Additionally, by directly pulling horizontally on the MDS with a force gauge, a measurement of approximately 6.1 lbs was taken. With a load of 34 lbs, this corresponds to a coefficient of friction of .175 for the frelon lined bearings. This was further reduced by adding SAE 20 lubrication, which is rated to cut friction in frelon by up to 50%. Smoother movement can be achieved by using linear ball bearings, which have an even lower coefficient of friction. It was also determined that the chair should turn at a minimum of 8 rpm.

Prototype 2 Testing Utilized for Initial Design of MDS

The key purpose of testing in Prototype 2 was to determine the ideal mass and displacement distances needed to achieve the desired speeds and accelerations of the chair. This was accomplished through an organized and sequential process to test different variables. Various masses were attached to the motor framework. Additionally, 50 pound sandbags were acquired to model the weight of a human, and were placed on top of the seat. The first test involved placing 100 pounds on top of the seat (2 sandbags), and a sum of masses on the MDS, totaling 16.3 pounds. The initial 100 pounds of weight served as a baseline for simulating the low end of possible user weight.

Procedure

Before placing the sandbags on top of the seat, the brakes were lifted up and the “zero” position of the seat was found, where the seat self-balances and becomes stationary on its own. This was found by attaching the motor to a 12 Volt battery source, and adjusting the position until the chair’s movement stopped. Once this position was found, the sandbags were placed on the seat, and subsequently adjusted until the seat once again wouldn’t displace itself, maintaining its zero position. With this configuration, the system was ready to test.

The position of the mass was displaced incrementally (approximately by 1 inch). The NINO device was then allowed to self-accelerate in an empty hallway from a stopped position until it reached its maximum speed. This speed was monitored using an app on a phone that



was connected to the device via Bluetooth. By measuring the time required to reach this speed and assuming constant acceleration, the acceleration of the device was calculated.

Various trials were performed for each displacement of the weight up until it reached its maximum displacement. After maximum displacement was reached, the “human” weight was increased from 100 to 150 pounds by adding an additional sandbag. The testing was repeated for different configurations of user weight and mass displacement.

Results and Discussion

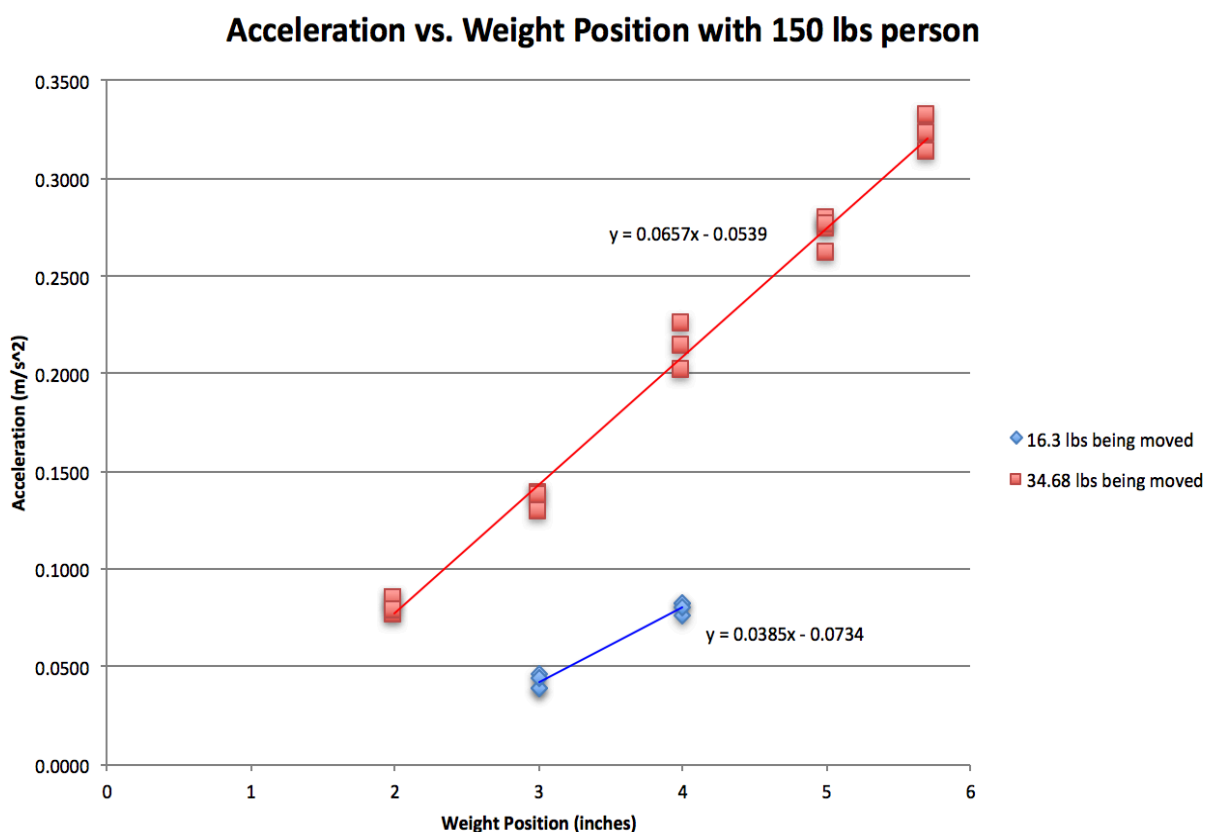


Figure 23 - Acceleration is plotted versus mass displacement, where a constant 150 lb user mass is used in both trials, while the mass displaced is varied.

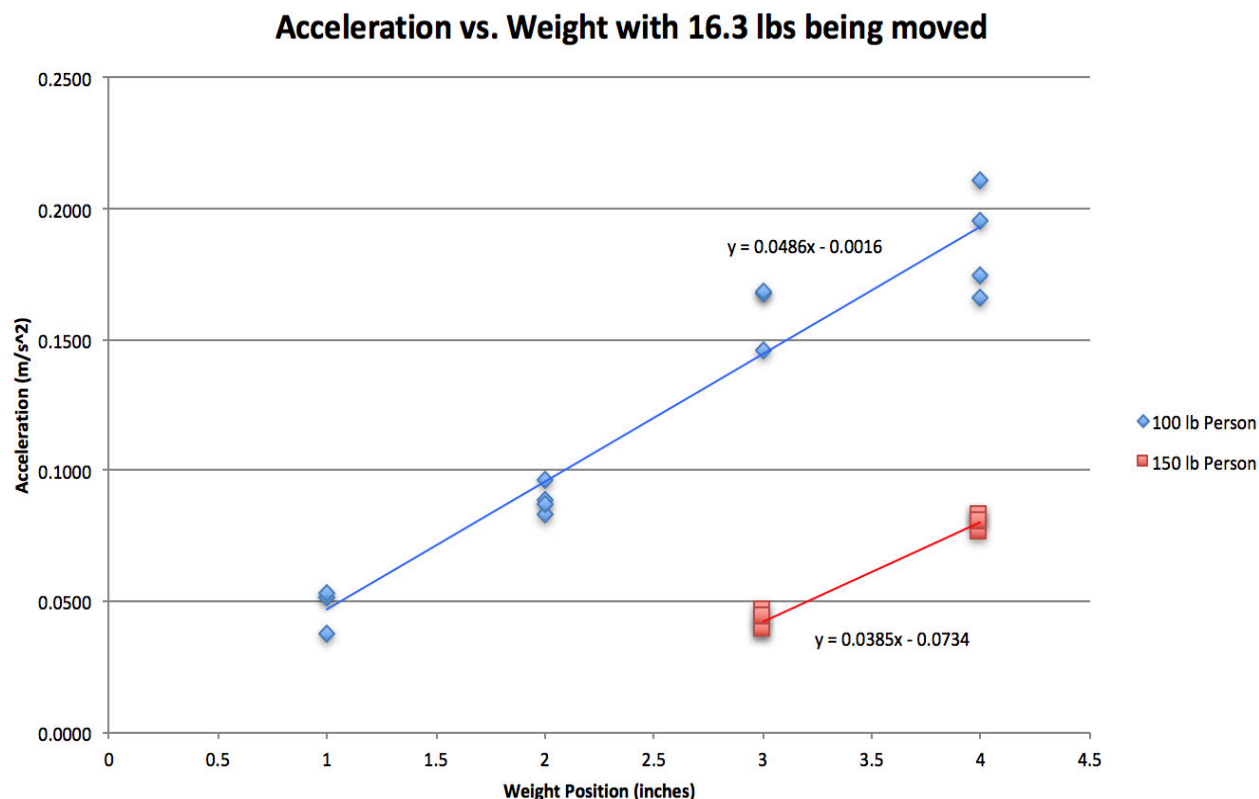


Figure 24 - Acceleration is plotted versus mass displacement, where a constant 16.3 lb mass is displaced in both trials, and the human mass is varied.

Figure 23 shows the data comparing 16.3 pounds to 34.68 pounds being displaced with a constant 150 lb mass placed on the seat. With the heavier of the two masses being displaced, the seat was capable of reaching accelerations and speeds much closer to what was desired. As a result, no more increases in mass were needed. Clear linear trends were evident for increasing accelerations with respect to increasing displacements of the mass attached to the MDS.

Figure 24 compares a 100-pound person vs. a 150-pound person, while displacing a 16.3-pound mass. It is evident from this graph that regardless of the weight of the user, the acceleration increases with an increasing displacement of the mass attached to the MDS, as is to be expected. Additionally, it is seen that for the same displacement of the 16.3 pounds, the device accelerates faster for the lighter human, which is to be expected. Based on these tests, it was obvious to NASHWHEELS that further testing needed to be implemented with a larger mass on the MDS being displaced, as the device couldn't reach high enough speeds with these mass configurations.

The testing also provided valuable information for choosing the desired weight moving forward. Knowing that the sponsor desired a speed of approximately 5 mph, it was calculated that this speed was achieved after displacing the 34.68 lb mass 2.7 inches with the 150 lb rider. This meant that for this rider weight, a moment of 94.6 in-lbs was necessary for our system.

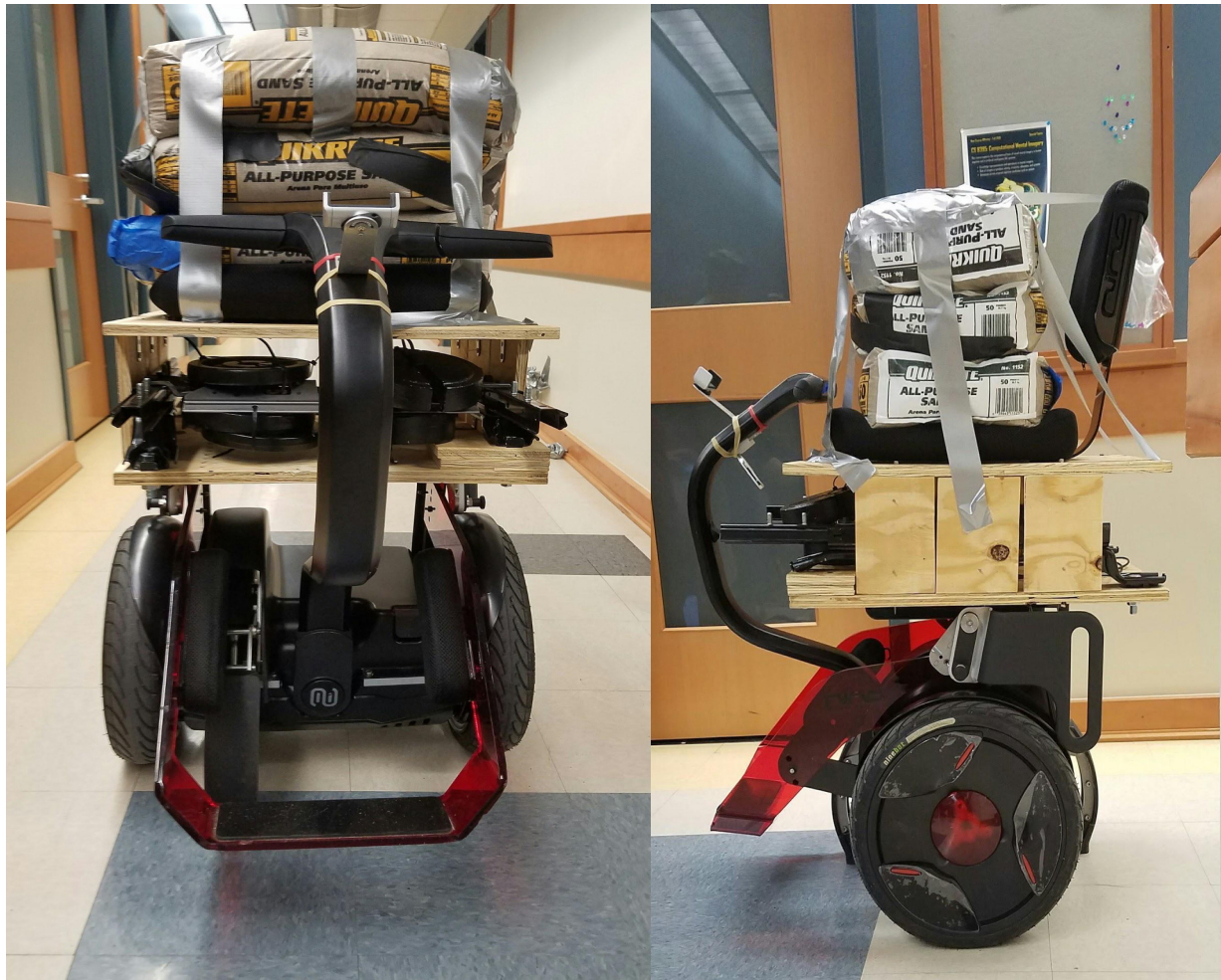


Figure 25 - Testing apparatus for Prototype 2.



Final Prototype Testing

Basic Validation of Design

Once the Final Prototype was built, it was important to verify that many of the basic features that the device was expected to have worked as they should. The following validation tests were performed:

- Chair turns in a 360° circle clockwise
- Chair turns in a 360° circle counterclockwise
- Chair turns in both directions above the minimum desired speed of 8 rpm
- Chair moves forwards
- Chair moves backwards
- Chair moves diagonally forwards and left
- Chair moves diagonally forwards and right
- Chair moves diagonally backwards and left
- Chair moves diagonally backwards and right
- MDS moves to extreme positions in both directions
- Limit switch in front halts motion of MDS moving forwards
- Limit switch in back halts motion of MDS moving backwards
- Hard stop in front stops MDS from moving forwards
- Hard stop in back stops MDS from moving backwards
- Verify MDS mass of 34 pounds

Decide on Optimal Seat Position

The NINO chair comes with seven seat positions that can be adjusted by adjusting screws. It was necessary to determine which of these positions offers the proper central gravity location when the user sits on it, having added our new components to the device. It was found that the position farthest towards the front offers the optimal position. This chair position allows for movement of the MDS forwards far enough from its zero position (when chair is stationary) to create a large enough moment for the user to reach maximum speed. This chair position also allows for movement of the MDS far enough backwards from its zero position (when chair is stationary) for the user to break in a reasonable amount of time. It was found that the MDS has 3.9 inches to move forwards and 1.7 inches to move backwards.

MDS Incline Testing

Oftentimes when the user initially sits in the chair, the vehicle will wobble for a few seconds as it calibrates its system. This wobbling is built in as a safety factor by NINO to help the user seat themselves in a balanced position. The wobbling also is initiated if the user is travelling in reverse at a high speed. Apart from these instances, the chair remains nearly vertical at all times, even when traversing inclines. To ensure that the MDS is always



operational, it was tested to ensure that even during the wobbling sequences, it would be able to operate and overcome the angle.

To perform the test, the wobbling was induced in the chair and its maximum angular tilting was observed and measured with motion capture technology. It was determined that the chair had a maximum tilt of 4 degrees in either direction as is depicted in Figure 26.

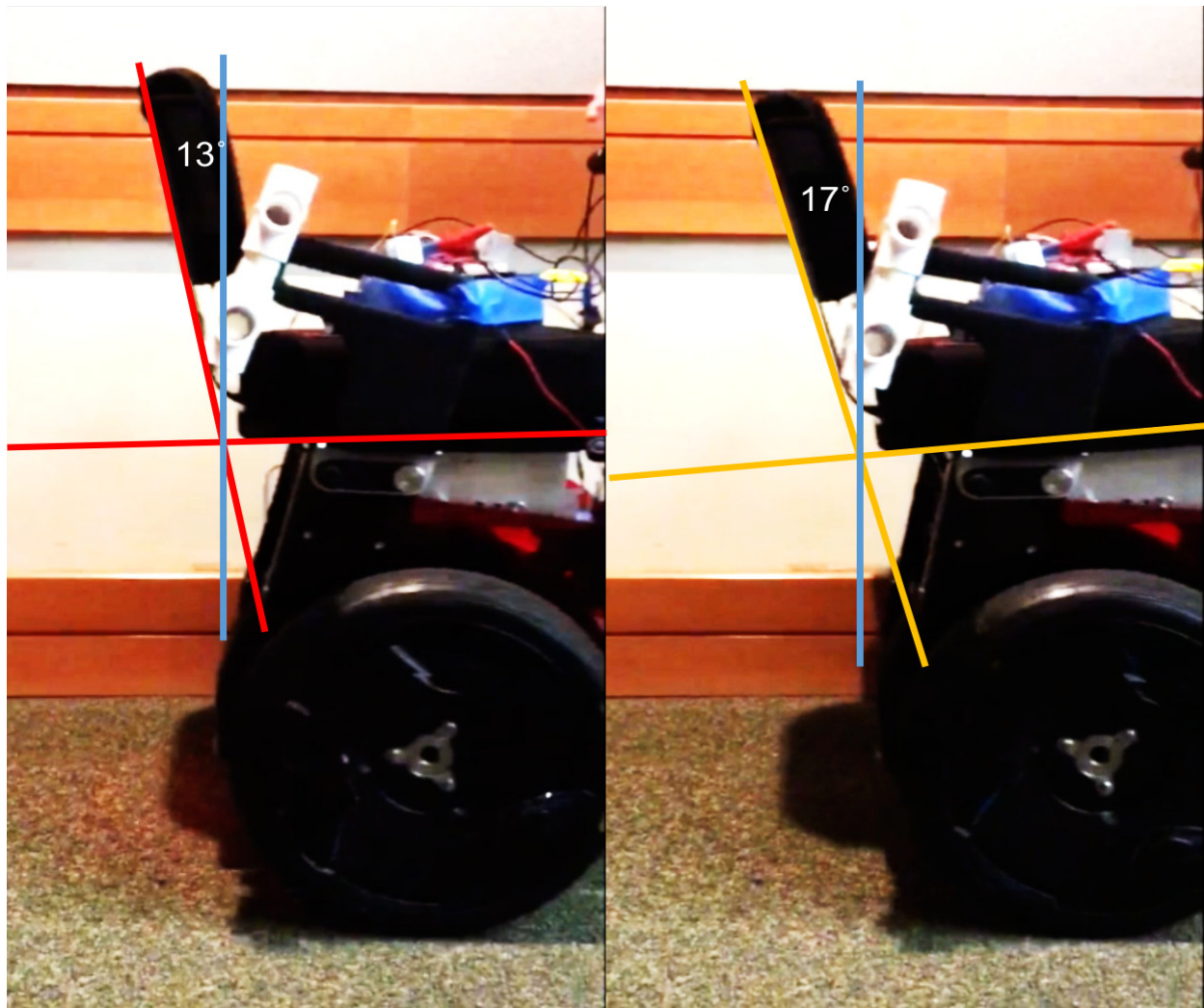


Figure 26 - On the left, the chair at its resting position. On the right, the chair after pitching backwards during a wobbling sequence.

The MDS design validation process began by removing the base from the vehicle so the seat could be accurately controlled separately. With the MDS attached, the seat was incrementally tilted on one side in steps of 1 degree. At each step, the MDS was turned on at maximum power and slid up the inclined shaft. Knowing that as the shaft became steeper the effects of gravity overcome the power of the motor, the MDS speed was not measured, but rather just the functionality, and the test was considered successful if the MDS could reach the top of the incline. After multiple iterations of testing for leaning forwards as well as backwards,



the MDS successfully passed the 4 degree requirement. Travelling uphill in the forward direction, the MDS achieved a maximum angle of 7 degrees. Travelling uphill in the reverse direction, the MDS was able to climb up to 8 degrees. Both of these nearly double the requirement, ensuring that even during the most intense wobbling sequences, the user is able to maintain control over the system.

MDS Speed Testing

The baseline requirement derived from Prototype 2 was that the MDS would have to produce a minimum moment of 94.6 in-lbs in roughly one second. With a 34 lb mass attached, this meant it would have to slide 2.78 in/s to achieve this goal. To validate the design, the MDS was loaded to achieve a total mass of 34 lbs, placed at one end of the track, and turned on at maximum power using the joystick. The time and total displacement was measured for various trials, and the test was repeated multiple times. The results of the testing can be seen below in Table 2 below. The average MDS Moment Rate going both forwards and backwards is significantly greater than the minimum of 94.6 in-lbs.

Table 2 - MDS Speed Testing Data

	Distance (in)	Time (s)	MDS Speed (in/s)	MDS Moment Rate (in-lb)
Forward	5.00	1.02	4.90	166.67
Forward	5.00	0.99	5.05	171.72
Forward	4.20	0.85	4.94	168.00
Backward	5.60	1.15	4.87	165.57
Backward	5.60	1.21	4.63	157.36
Backward	5.60	1.29	4.34	147.60
Avg Forward	4.73	0.95	4.97	168.81
Avg Backward	5.60	1.22	4.60	156.49

Testing with Various User Masses

Sand bags totalling 60, 120, and 180 pounds were placed on the chair, and testing with each mass was performed. First, the basic validation of design points, previously mentioned, were all verified at each user mass. Following this, the maximum speed and braking times in each scenario were tested, with the results displayed in Table 3 below.

Table 3 - Data for testing with various user masses

Weights (lbs)	MDS Position Relative to Zero Position (in)	Max Speed (mph)	Braking time (3 to 0 mph) (s)
60	0	0	0
60	3.9	6.1	3.06
120	0	0	0
120	3.9	4.5	4.17
180	0	0	0
180	3.9	3.05	4.5



Additionally, chair speed was plotted against both MDS position and moment created by the MDS position for all three masses. The relationships can be seen in Figures 27 and 28.

Chair Speed vs. MDS Position

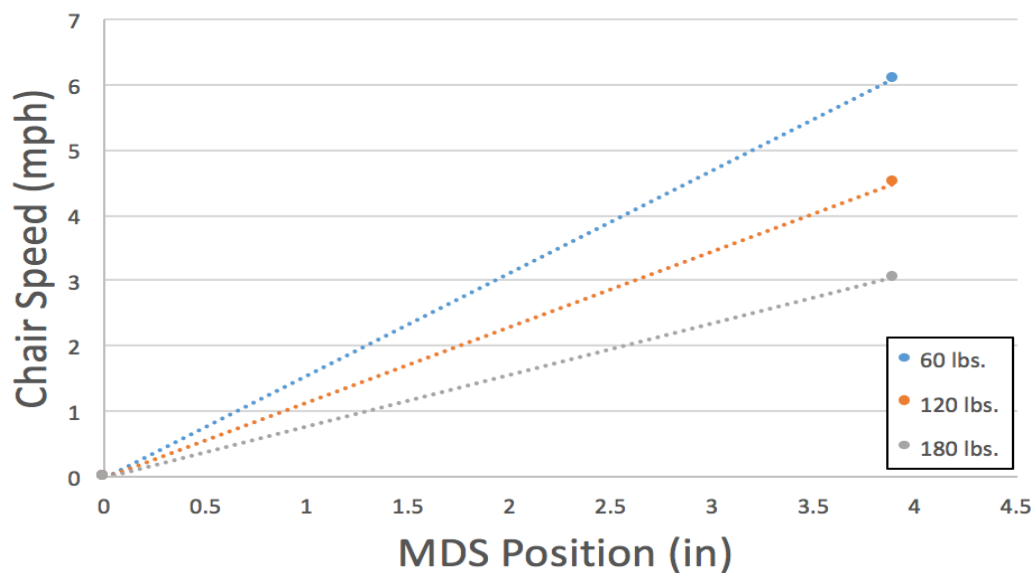


Figure 27 - Chair speed as a function of MDS position.

Chair Speed vs. Moment

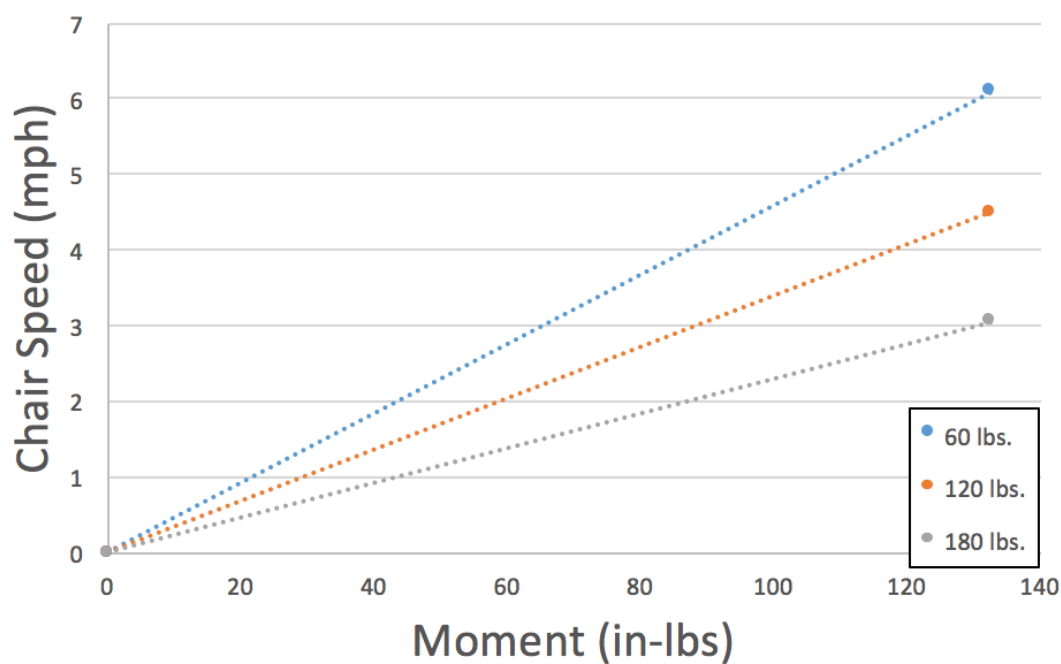


Figure 28 - Chair speed as a function of moment.



Steering Calibration Data

Steering was calibrated by changing the pulse width sent to the servo motor that spun the dual-magnet about the hall effect sensor. It was found that a range of 13.88° was necessary in order for the chair to turn at appropriate speeds of about 8 rpm in each direction. This range was accomplished by sending pulse widths to the motor that would allow for it to move $\pm 6.94^\circ$ from its zeroed position. Trial and error allowed for determination of this data.

Validation of Design

The results of Final Prototype testing indicated that the auxiliary mass design is effective in accelerating the NINO Robotics Wheelchair and the steering can be effectively controlled with the joystick. It was found that the 34-pound auxiliary mass configuration proved to be sufficient in meeting the desired speed of the vehicle. The MDS system, including the shafts and rack setup, added a total mass of 40 lbs to the chair, which brings the total weight of the chair to be 120 lbs. With the external MDS system, the maximum user weight has been reduced to 180 lbs.

The MDS designed is 12" x 9" x 8.5" and fits perfectly under the space beneath the seat plate. Without any user, the COG position of the MDS is 3.9 inches away from the front of the seat plate, which provides ample track length for sliding the MDS. This will simulate the user leaning motion and provide sufficient motion to acquire the desired forwards or backwards acceleration. The MDS can reach a maximum incline of 7 degrees. Despite the chair staying upright at all time thanks to the gyroscopic technology embedded in the base, the MDS incline testing is essential in making sure the system does not fail or slide during the momentary wobble when the brakes are initially removed. The maximum MDS incline of 7 degrees is sufficient to compensate for the $\pm 4^\circ$ of wobble.



Finite Element Analysis testing of MDS

The CAD model of the current Mass Displacement System (MDS) was analyzed in Finite Element Analysis through ANSYS. The mesh of the assembly can be seen in Figure 29 below. Proper element sizes and shapes were verified via h-refinement, where elements were decreased in size until convergence of solution was verified. The model was then constrained by boundary conditions, where the MDS was fixed along its bearing axes. A 25-pound load (representing the masses attached) was then uniformly applied across both hole on the side plates. With this setup, various analyses could be performed, including deformation, stresses, fatigue life, and safety factor, all of which can be seen in Figures 30-33 on the following pages.

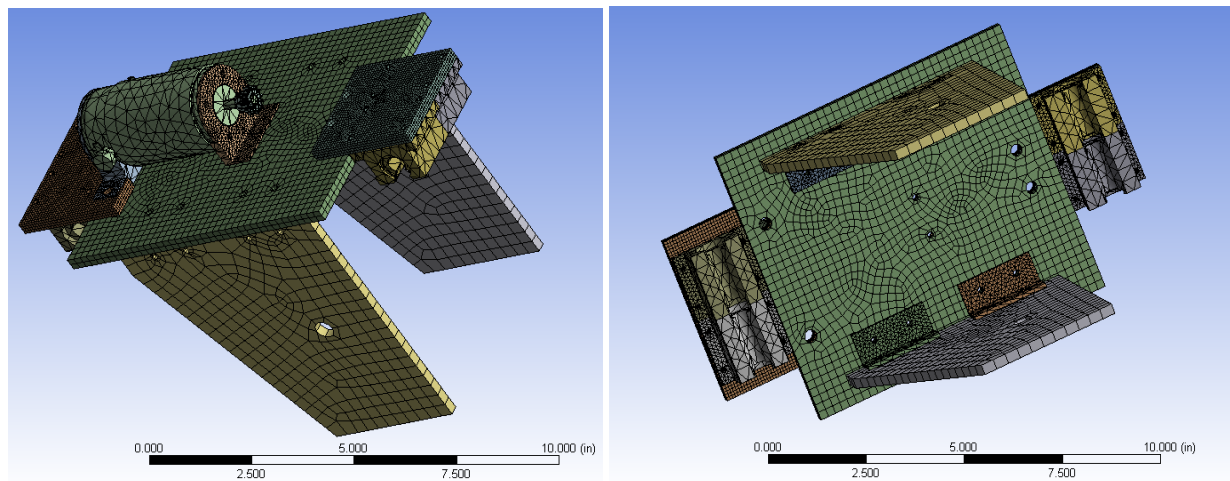


Figure 29 - Mesh of MDS.

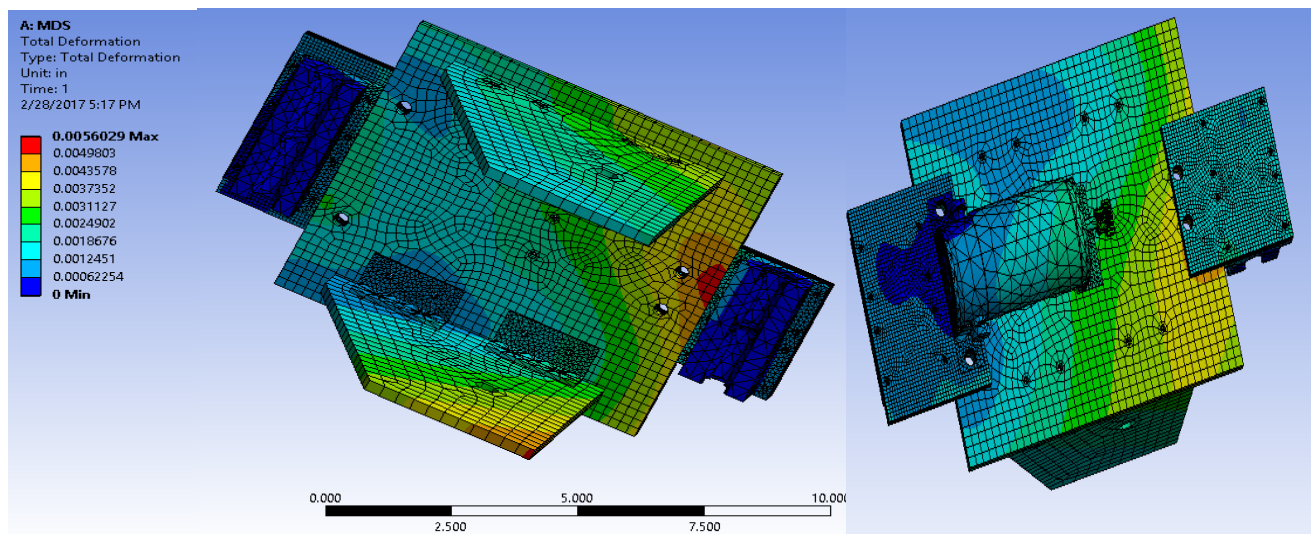


Figure 30 - Total deformation of MDS.

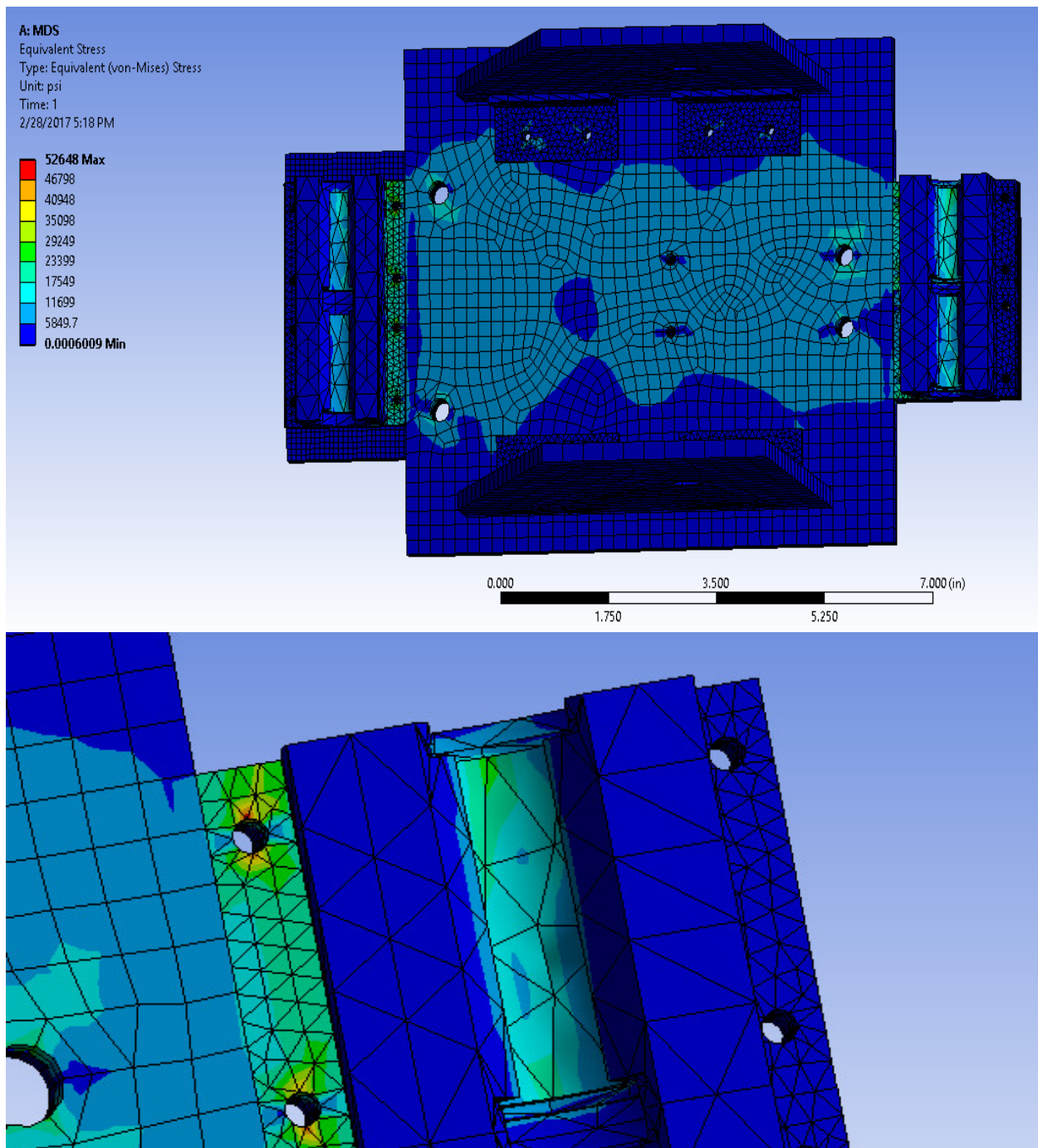


Figure 31 - Equivalent stress of MDS, where bottom portion shows zoomed in point of interest.

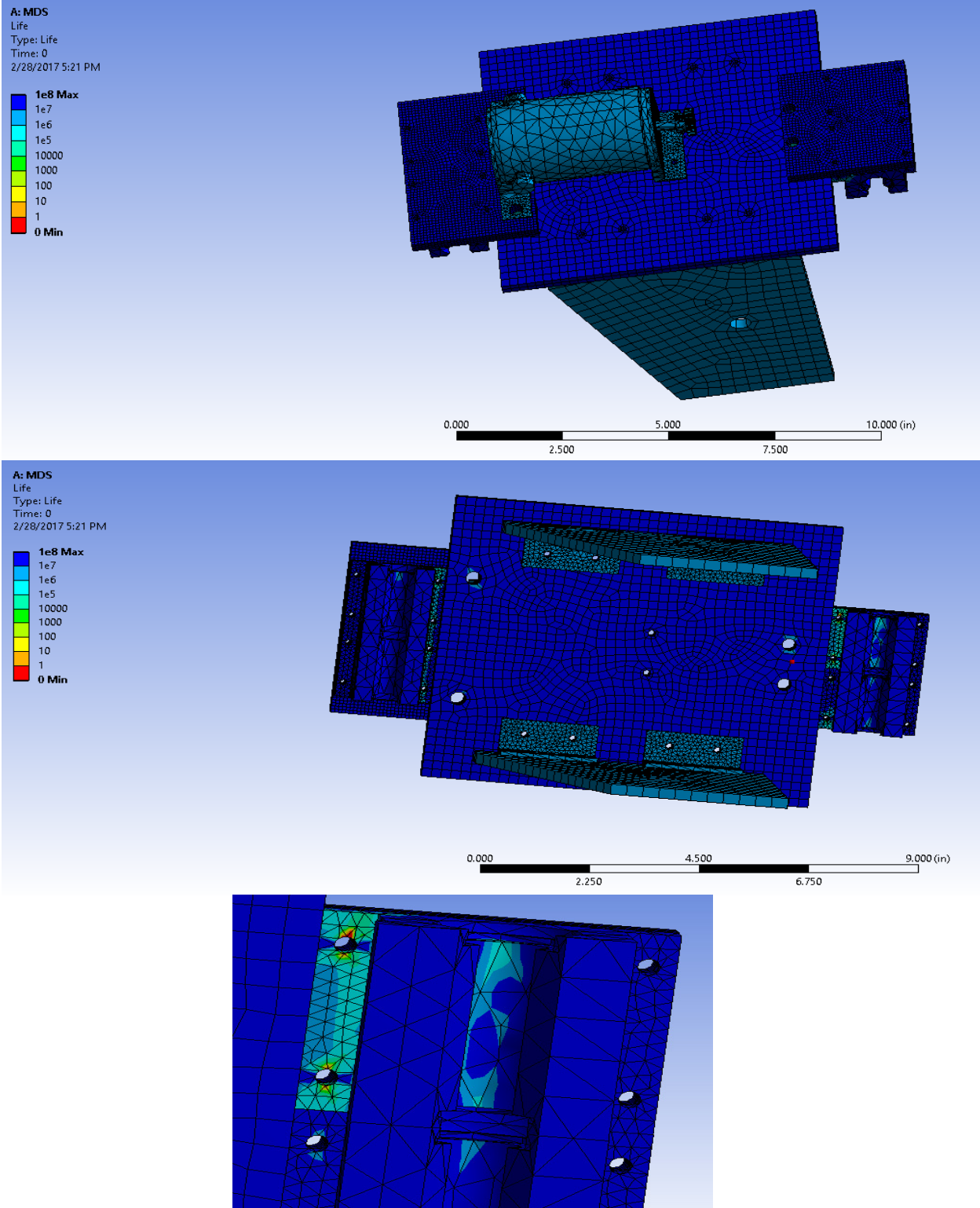


Figure 32 - Life (in cycles) of MDS, where bottom third shows point of interest.

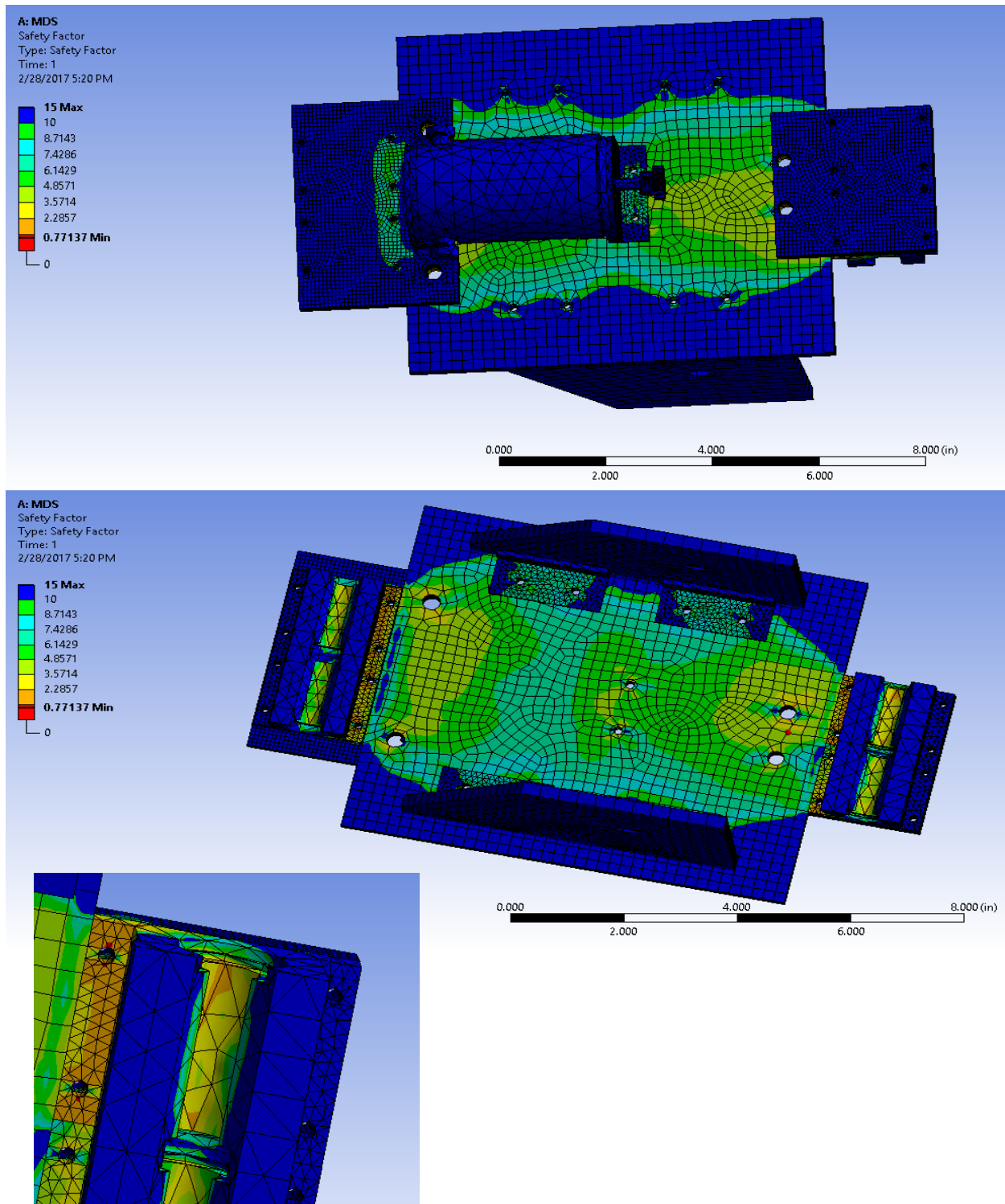


Figure 33 - Safety factor of MDS, where bottom third shows point of interest.

The figures above exhibit the results from the FEA analysis. First, as seen in Figure 30, deformation is minimal throughout the assembly. Maximum deformation is .0056 inches, and this occurs at the junction of the bearing plate and the main housing. This deformation is



minimal, and does not affect the performance of the MDS. The next figure, Figure 31, illustrates the stresses that occur within the plates. As seen, the maximum stress that occurs is about 52.6 ksi, and this occurs in 2 bolted locations, as seen in the bottom of Figure 31. These two holes turn out to be a location of issue and interest throughout the further FEA analysis. As is the case with all FEA testing, the results obtained must be placed into the context of real world testing. With testing of the device, no cracking or yielding has occurred in these holes. Likely, ANSYS has not fully constrained this area properly, which leads to the anomalous values that occur. With this in mind, the remaining analysis is performed.

Looking back at Figure 31, it is seen that the stress that occurs in all areas except these two anomalous holes falls below aluminum's yield stress of 35 ksi, meaning the MDS will hold up. Next, the life of the MDS was tested in Figure 32. Once again, ignoring these two anomalous holes, it is found that the rest of the MDS will hold up for 10^6 cycles, which provides a valid design life. Finally, safety factor is analyzed in Figure 33, and it is seen that a safety factor of about 2.5 and above is implemented throughout most areas of the plates (minus the troubling area). All in all, these results verify the design of the MDS, ensuring it will not fail during use.



Bill of Materials

Table 4 - Bill of Materials for mechanical parts

Part	Manufacturer	Part #	Qty	Unit	Unit Cost	Total Cost	Supplier
Sliding Mass Mechanism							
Two-Piece Support Rail Shaft	PBCLinear	59585K83	1	1	\$64.48	\$64.48	MMC
Self Aligning Linear Bearing	PBCLinear	6374K313	2	1	\$64.75	\$129.50	MMC
Fixed Alignment Linear Bearing	PBCLinear	8649T13	2	1	\$61.16	\$122.32	MMC
Rack	UniGear	7854K15	1	1	\$39.67	\$39.67	MMC
Pinion	UniGear	6832K59	1	1	\$14.90	\$14.90	MMC
6061 Aluminum Flat (Wall Housing)	Ledford Steel Co	F4124	2	1	\$14.69	\$29.38	MetalsDepot
6061-T651 Aluminum Plate (Mass Housing)	Ledford Steel Co	P314T6	3	1	\$23.30	\$69.90	MetalsDepot
6061 Aluminum Flat (Bearing Plate)	Ledford Steel Co	F4383	1	1	\$11.91	\$11.91	MetalsDepot
6061-T6 Aluminum Angle (Shaft Bracket)	Ledford Steel Co	A3218	2	1	\$8.84	\$17.68	MetalsDepot
#5-40 Thread Head Screw	Bolt and Nut Inc	90128A863	2	10	\$5.38	\$10.76	MMC
#5-40 Thread Nut	Bolt and Nut Inc	90480A006	1	100	\$1.71	\$1.71	MMC
#6-32 Thread Head Screw	Bolt and Nut Inc	91251A144	1	100	\$8.46	\$8.46	MMC
#6-32 Thread Nut	Bolt and Nut Inc	90480A007	1	100	\$1.24	\$1.24	MMC
#8-32 Thread Head Screw	Bolt and Nut Inc	91251A199	1	50	\$7.63	\$7.63	MMC
#8-32 Thread Nut	Bolt and Nut Inc	90480A009	1	100	\$1.60	\$1.60	MMC
#8-36 Thread Head Screw	Bolt and Nut Inc	91251A829	1	25	\$9.00	\$9.00	MMC
#8-36 Thread Nut	Bolt and Nut Inc	90480A185	1	100	\$2.51	\$2.51	MMC
5/16"-18 Hex Head Screw	Bolt and Nut Inc	92620A581	1	50	\$8.61	\$8.61	MMC
5/16"-18 Socket Head Screw	Bolt and Nut Inc	91251A581	1	50	\$8.39	\$8.39	MMC
5/16"-18 Nut	Bolt and Nut Inc	90499A030	1	100	\$4.18	\$4.18	MMC
1/2-20 Hex Nuts	Bolt and Nut Inc	94895A825	1	50	\$8.20	\$8.20	MMC
3/8"-24 Hex Head Screw	Bolt and Nut Inc	92240A354	2	10	\$3.46	\$6.92	MMC
3/8"-24 Nut	Bolt and Nut Inc	94191A350	2	10	\$5.31	\$10.62	MMC
2 Hole 90 Degree Angle Bracket (Wall Housing)	Thomas & Betts Corp	ZAB201EG-10	4	1	\$1.41	\$5.64	HomeDepot
Wide Corner Brace (Mass Housing)	Stanley National	STA-N351-483	4	1	\$2.48	\$9.92	HardwareHut
Masses (10 lbs Dumbbell Plate)	CAP Barbell	RPG-007.5#2	3	1	\$13.40	\$40.20	Walmart
Threaded Rod	PBCLinear	47069	1	1	\$14.56	\$14.56	Fastenal
Motor Bracket	Custom	3D Printed	2	1	\$5.00	\$10.00	MakerBot
Rack Spacer	Custom	3D Printed	3	1	\$2.00	\$6.00	MakerBot
4" x 7/8" 115 Corner Brace	Stanley Hardware	N220-145	1	1	\$2.87	\$2.87	Lowe's
TOTAL						\$678.76	



Table 5 - Bill of Materials for electronic parts and NINO chair

Part	Manufacturer	Part #	Qty	Unit Cost	Total Cost	Supplier
Electronics Control						
Motor	Pittman-Motors	6331K13	1	\$99.53	\$99.53	MMC
60V to 12V Voltage Converter	SMAKN	B00XKLH77K	1	\$18.00	\$18.00	Amazon
9V Battery	Energizer	522BP-2	1	\$12.01	\$12.01	Amazon
3 Pins Molex Connector	Molex	22-01-3037	1	\$0.15	\$0.15	Newark
#22 AWG (300 Volts)	BulkWire	Wire-ST-22-00-	50 ft	\$0.07	\$3.50	BulkWire
Arduino Uno R3	Arduino	Uno R3	1	\$24.95	\$24.95	AdaFruit
PFETS	On Semiconductor	FQP27P06-ND	2	\$1.34	\$2.68	SparkFun
NFETS	On Semiconductor	FQP30N06L	2	\$1.12	\$2.24	SparkFun
BJT	On Semiconductor	BC846BDW1T1	2	\$0.23	\$0.46	SparkFun
10K Resistor	Yageo	CFR-25JB-52-1	4	\$0.10	\$0.40	SparkFun
Heat Sinks	Addicore	B00HPQGTI4	4	\$1.50	\$6.00	SparkFun
Joystick	DirectIndustry	HCARDU0019	1	\$1.99	\$1.99	SparkFun
Terminal Connector	Dorman	EL-14073	1	\$2.99	\$2.99	DigiKey
Printed Circuit Board	Custom	N/A	1	\$10.00	\$10.00	ProtoMat
PCB Housing	Custom	3D Printed	1	\$3.50	\$3.50	MakerBot
Battery Housing	Custom	3D Printed	1	\$1.50	\$1.50	MakerBot
Limit Switches	OMRON	SS-5GL13T	2	\$1.76	\$3.52	Dr. Withrow
PCB Circuitry	Custom	Custom Made	1	\$20.00	\$20.00	VUSE
Servo Motor	Tower Pro	SG-5010 - 5010	1	\$12.00	\$12.00	AdaFruit
TOTAL					\$225.42	
Part	Manufacturer	Part #	Qty	Unit Cost	Total Cost	Supplier
Nino Robotics Smart Chair	Nino Robotics	N/A	1	\$8,995.00	\$8,995.00	Bike-On
TOTAL					\$8,995.00	

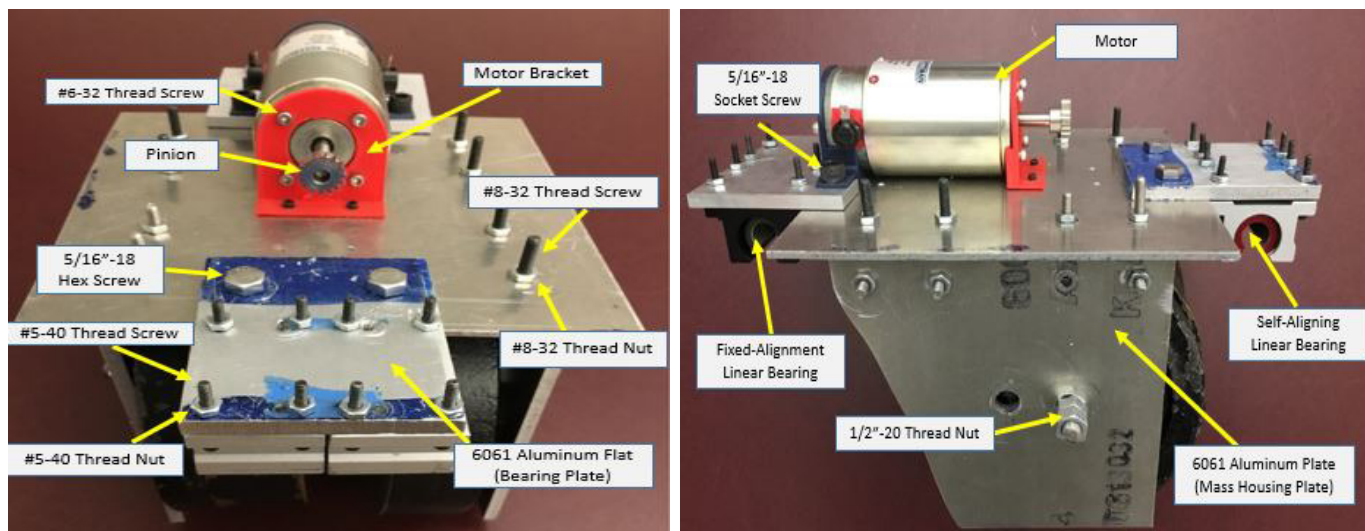


Figure 34 - MDS components.

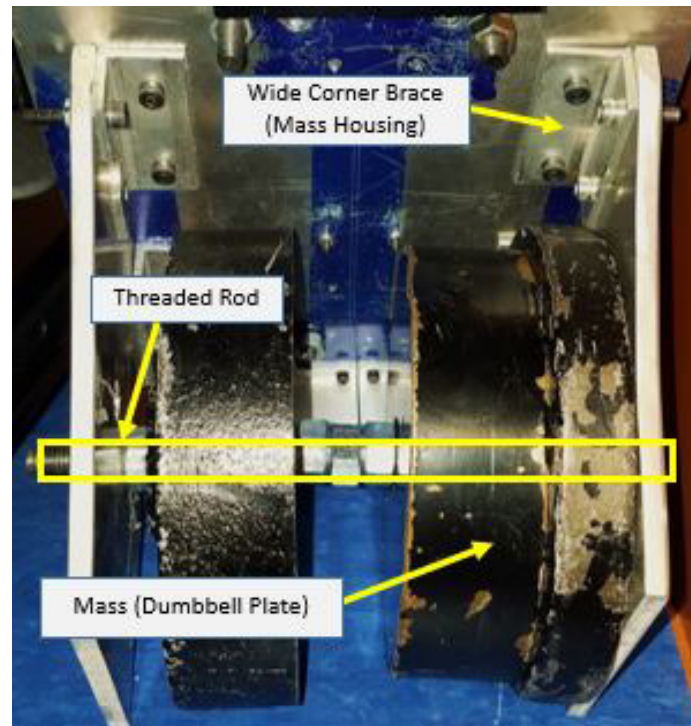


Figure 35 - Mass assembly components.

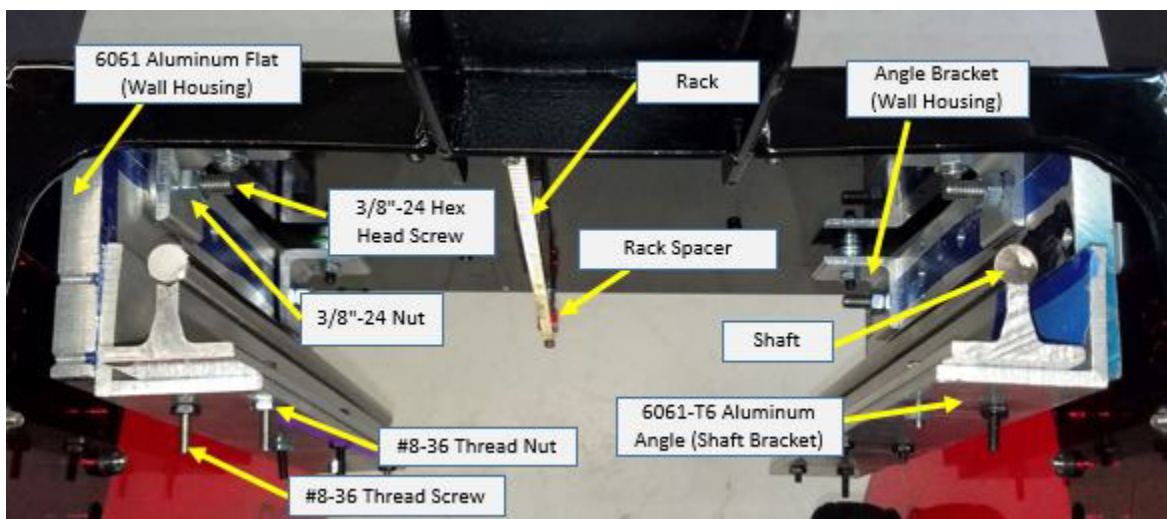


Figure 36 - Shaft and rack assembly components, located in cavity beneath chair.

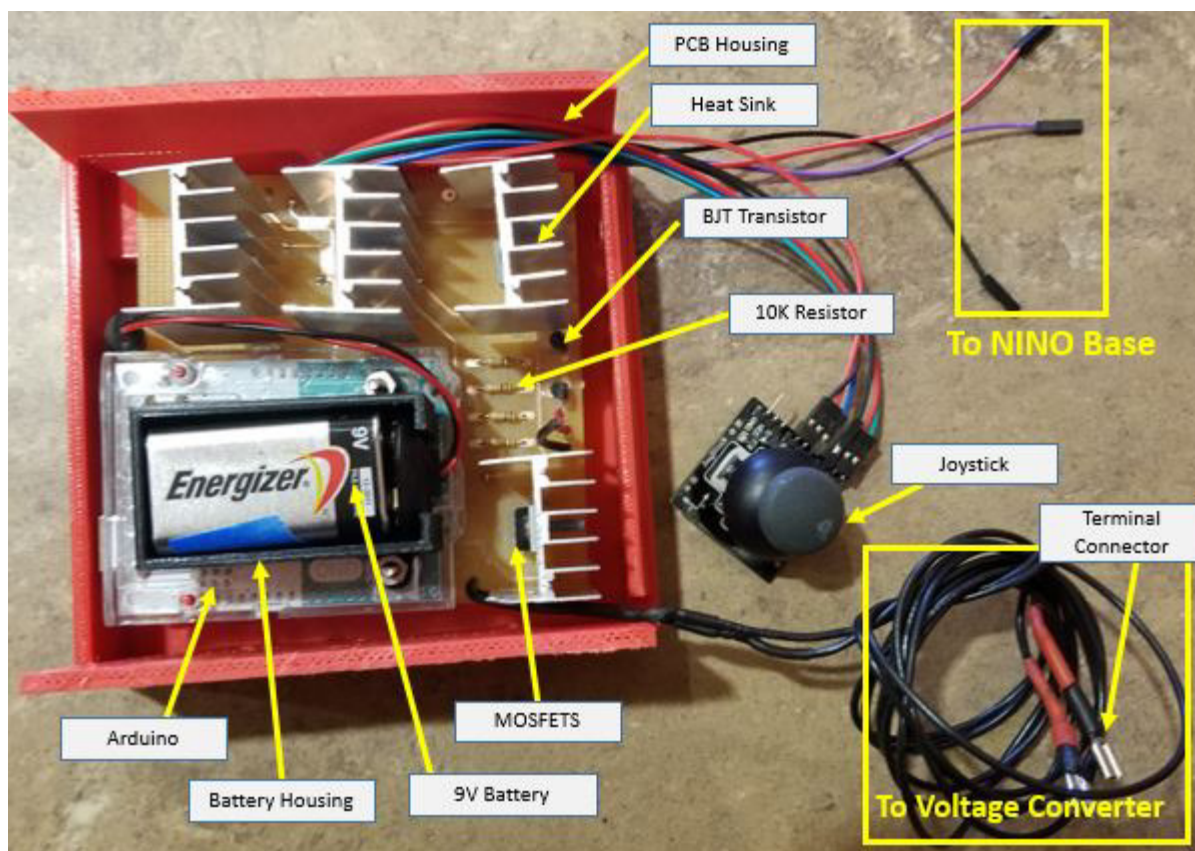


Figure 37 - PCB and electronic components inside housing.



Budget

Table 6 - Project budget by prototype

Item	Qty	Total Cost	Supplier	Who Paid	Prototype
Prototype 1					
Housing (MDF)	1	\$14.99	FullSpectrum	Vanderbilt	1
Rack and Pinion (MDF)	1	\$2.50	FullSpectrum	Vanderbilt	1
Rails (PVC Pipe)	2	\$4.30	NationalPipe	Vanderbilt	1
9V DC Motor	1	\$8.80	MMC	Vanderbilt	1
Brackets arm (3D Print)	2	\$2.00	MakerBot	Vanderbilt	1
Prototype 2					
Power Seat Track	1	\$100.00	Nissan	Maddie	2
50 lbs Sand Bags	3	\$12.00	Quikrete	Vanderbilt	2
10 lbs Weights	3	\$30.00	Quikrete	Vanderbilt	2
Plywood	2	\$3.69	MTEWood	Vanderbilt	2
Prototype 3					
12V DC Motor	1	\$99.53	MMC	Max Mobility	3
Two-Piece Support-Rail Shaft	1	\$64.48	MMC	Max Mobility	3
Self-Aligning Linear Sleeve Bearing	2	\$129.50	MMC	Max Mobility	3
Wall Housing Plate	2	\$29.38	MetalsDepot	Vanderbilt	3
6061-T651 Aluminum Plate	3	\$69.90	MetalsDepot	Vanderbilt	3
6061 Aluminum Flat	1	\$11.91	MetalsDepot	Vanderbilt	3
6061-T6 Aluminum Angle	2	\$17.68	MetalsDepot	Vanderbilt	3
#5-40 Thread Head Screw	2 Pckt	\$10.76	MMC	Vanderbilt	3
#5-40 Thread Nut	1 Pckt	\$1.71	MMC	Vanderbilt	3
#8-32 Thread Head Screw	1 Pckt	\$7.63	MMC	Vanderbilt	3
#8-32 Thread Nut	1 Pckt	\$1.60	MMC	Vanderbilt	3
#8-36 Thread Head Screw	1 Pckt	\$9.00	MMC	Vanderbilt	3
#8-36 Thread Head Screw	1 Pckt	\$2.51	MMC	Vanderbilt	3
#6-32 Thread Head Screw	1 Pckt	\$8.46	MMC	Vanderbilt	3
#6-32 Thread Nut	1 Pckt	\$1.24	MMC	Vanderbilt	3
5/16"-18 Hex Head Screw	1 Pckt	\$8.61	MMC	Vanderbilt	3
5/16"-18 Socket Head Screw	1 Pckt	\$8.39	MMC	Vanderbilt	3
5/16"-18 Nut	1 Pckt	\$4.18	MMC	Vanderbilt	3
1/2-20 Hex Nuts	1 Pckt	\$8.20	MMC	Vanderbilt	3
3/8"-24 Hex Head Screw	2 Pckt	\$6.92	MMC	Vanderbilt	3
3/8"-24 Hex Head Screw	2 Pckt	\$10.62	MMC	Vanderbilt	3
Brackets (Wall Housing)	4	\$5.64	MakerBot	Vanderbilt	3
Brackets (Motor Housing)	4	\$9.92	MakerBot	Vanderbilt	3
Masses (Dumbbell Plate)	5	\$40.20	Walmart	Vanderbilt	3
Threaded Rod	1	\$14.56	Fastenal	Vanderbilt	3



Table 7 - Project budget by prototype (cont.)

Prototype 3					
Motor Bracket (3D Print)	2	\$10.00	MakerBot	Vanderbilt	3
12V Battery	1	\$35.00	Amazon	Vanderbilt	3
Arduino UNO R3	1	\$24.95	Adafruit	Syakirah	3
Breadboard	1	\$8.40	DigiKey	Vanderbilt	3
Single Core Wires	1	\$2.00	DigiKey	Vanderbilt	3
Heat Sinks	4	\$6.00	Sparkfun	Vanderbilt	3
Joystick	1	\$1.99	Sparkfun	Vanderbilt	3
L298N H-Bridge	3	\$14.50	OddWires	Syakirah	3
P-MOSFET	2	\$2.68	Sparkfun	Vanderbilt	3
N-MOSFET	2	\$2.24	Sparkfun	Vanderbilt	3
NPN Transistor	2	\$0.46	Sparkfun	Vanderbilt	3
10K Resistor	4	\$0.40	Vanderbilt	Vanderbilt	3
9V Battery	4	\$11.97	Walmart	Jeremy	3
Prototype 4					
Fixed-Alignment Linear Sleeve Bearing	2	\$122.32	MMC	Max Mobility	4
Magnets	8	\$7.60	Sparkfun	Max Mobility	4
Hall Effect Sensor	4	\$8.00	Adafruit	Max Mobility	4
Wire	1	\$5.00	Walmart	Shiekh	4
.625" Gear	1	\$14.90	MMC	Max Mobility	4
60V to 12V DV Converter	1	\$18.00	Amazon	Max Mobility	4
Rack Spacer (3D Print)	3	\$6.00	MakerBot	Vanderbilt	4
Electronics Housing (3D Print)	1	\$3.50	MakerBot	Vanderbilt	4
Battery Housing (3D Print)	1	\$1.50	MakerBot	Vanderbilt	4
Printed Circuit Board	1	\$10.00	ProtoMat	Vanderbilt	4
Final Prototype					
Limit Switches	2	\$3.52	Dr. Withrow	Vanderbilt	Final
Servo Motor	1	\$12.00	Adafruit	Jordan	Final
4" x 7/8" 115 Corner Brace	1	\$2.87	Lowes	Vanderbilt	Final
9V Batteries	5	\$10.00	Rite Aid	Shiekh	Final
TOTAL COST		\$1,183.14			

Table 8 - Total budget

Prototype	Average Number of Hours Spent per Person	Total Number of Group Hours
1	43.1	215.5
2	34.3	171.5
3	55.2	276
4	78.9	394.5
Final	54.1	270.5
Total Hours	265.6	1,328.00
Hour Cost		\$20/hour
Total Hour Cost		\$26,560.00
Total Material Cost		\$1,183.14
TOTAL COST		\$27,743.14



Conclusions and Final Plans

NASHWHEELS has planned, designed, built, iterated, and tested five different prototypes, with each one contributing to the building of the next.

Prototype 1 featured the idea of moving the entire seat forwards and backwards to eliminate the need of tilting by the user. Prototype 1 also considered several linear motion systems - rack and pinions, 2 bar linkages, and linear actuators. A rack and pinion gear was chosen as the system, as it provides the smoothest linear motion based on the testing done on Prototype 1.

NASHWHEELS' Prototype 2 featured a fundamental shift in the concept design as an auxiliary mass displacement system was chosen over moving the entire seat. This prototype was then built using a power automotive car seat with weights attached. The main purpose of Prototype 2 was to test the reliability of the concept design. After verifying that the system worked, the testing proceeded to find how much mass was necessary and how far the mass needed to be displaced to achieve the desired acceleration for the targeted user weight. The data obtained showed that a moment of 94.6 in-lbs was needed to achieve the desired accelerations.

Prototype 3 features a mass displacement system attached beneath the existing NINO Robotics chair seat, equipped with external controls. The main advantages of this design included having significantly less power required in the motor to move the mass compared to moving the whole seat, as well as less overall volume required for the design. With the MDS beneath the chair, sliding the auxiliary mass did not affect the user, providing the best experience by eliminating direct jerky motion of the seat. Another major advantage of this design is moving an auxiliary mass, which can be designed and applied to any 2-wheel DCOG vehicle. However, the Prototype 3 mass displacement system provided inconsistent and unreliable data, where the mass linear motion was not smooth.

Prototype 4 featured a few key advancements, the first of which was a large increase in the reliability of the MDS. This included a change in some bearing types as well as an implementation of extra bearings on each side, creating a more level plane for the MDS to slide on, and maneuvering the motor to a more ideal location. Steering control was also first introduced with Prototype 4, with control being accomplished by sending a voltage directly from the Arduino to the chair's steering board. Both MDS and steering control were combined into a single circuit, which was then converted in a PCB. Prototype 4 offered the first glimpse into joystick control for both MDS and steering control, but reliability was low and the device would often malfunction.

The Final Prototype integrated many of the solutions from the previous four prototypes, while adding reliability and consistency to all controls. The method of steering was changed to control via moving a dual-magnet about a hall effect sensor by spinning a servo motor.



Additionally, limit switches and hard stops were added to both ends of MDS movement. The PCB was finalized, and all internal circuitry was contained within a 3D printed box which was bolted to the front of the chair.

At this point, this iteration of design is considered to be the Final Prototype, and a shift in focus has been made to preparing for design day. A video production that promotes the newly improved NINO Chair will be finalized to market the NASHWHEELS product, while ensuring its bright future. NASHWHEELS will also finalize a poster that shows the significance of the project, and explains how the product works. Finally, each team member will be prepped and ready to present on all aspects of the product for design day.

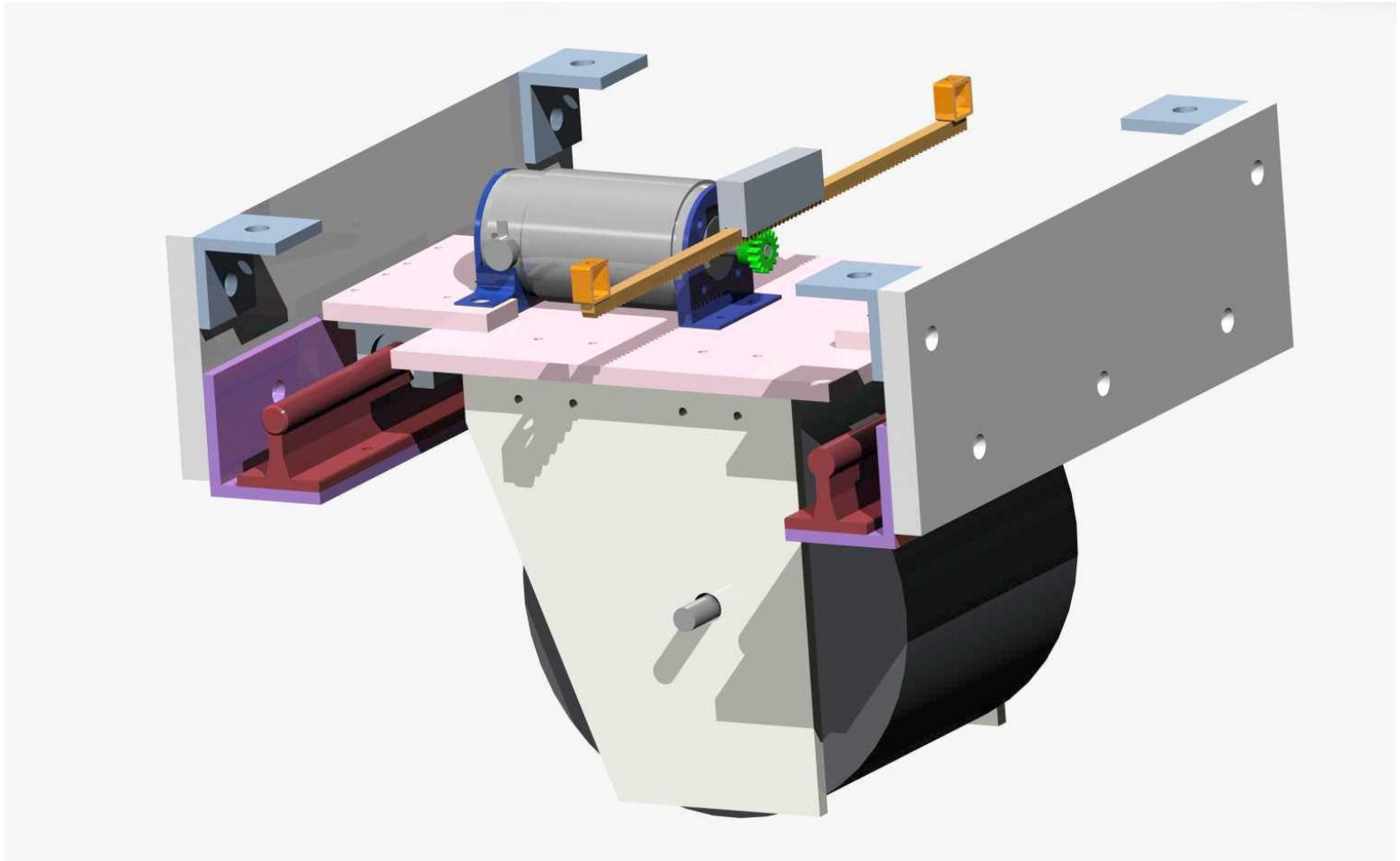


References

- [1] NINO Robotics, 'NINO Robotics: Gallery', [Online]. Available: <http://www.NINO-robotics.com/en/galerie-NINO/>
- [2] http://www.segway.com/media/1195/24010-00001_aa_se_um_en_usb_user-manual.pdf
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- [4] segfree.co.za
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- [6] Engineers Edge, 'ANSI External Screw Threads Size & Tolerance Chart', [Online]. Available: http://www.engineersedge.com/screw_threads_chart.htm



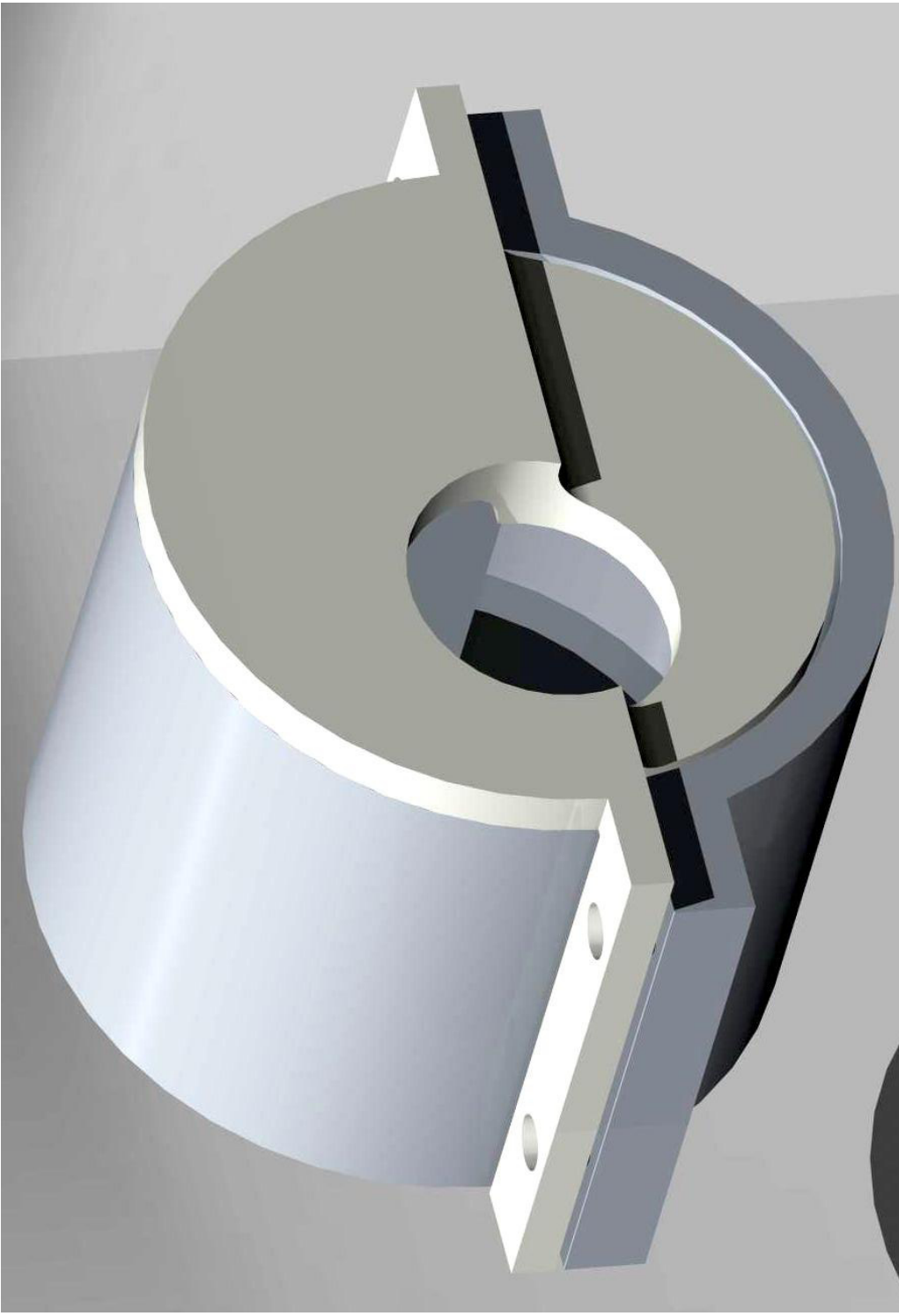
APPENDIX A: CAD Models



Final Prototype CAD



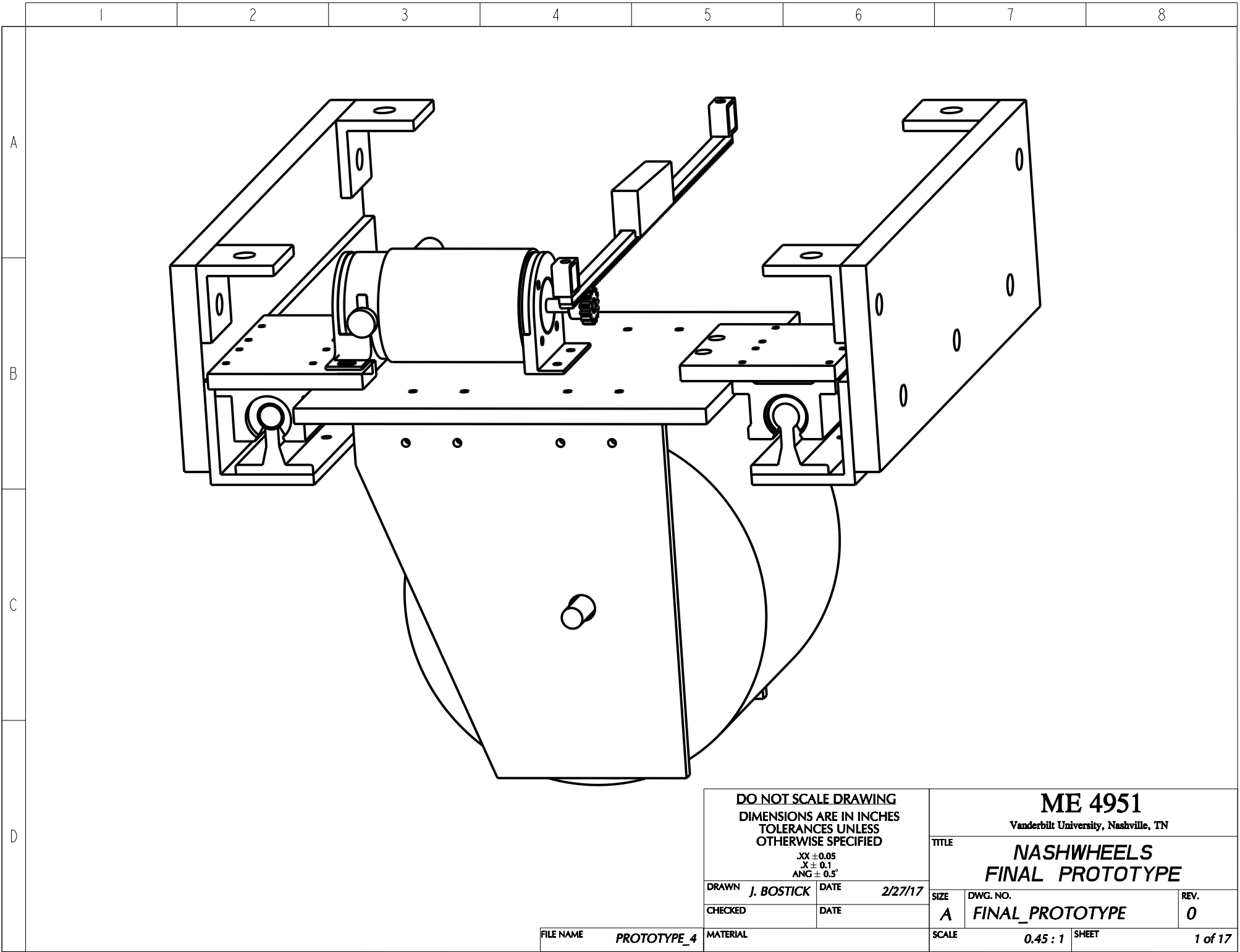
Electronics Housing CAD



Steering Assembly CAD



APPENDIX B: Technical Drawings

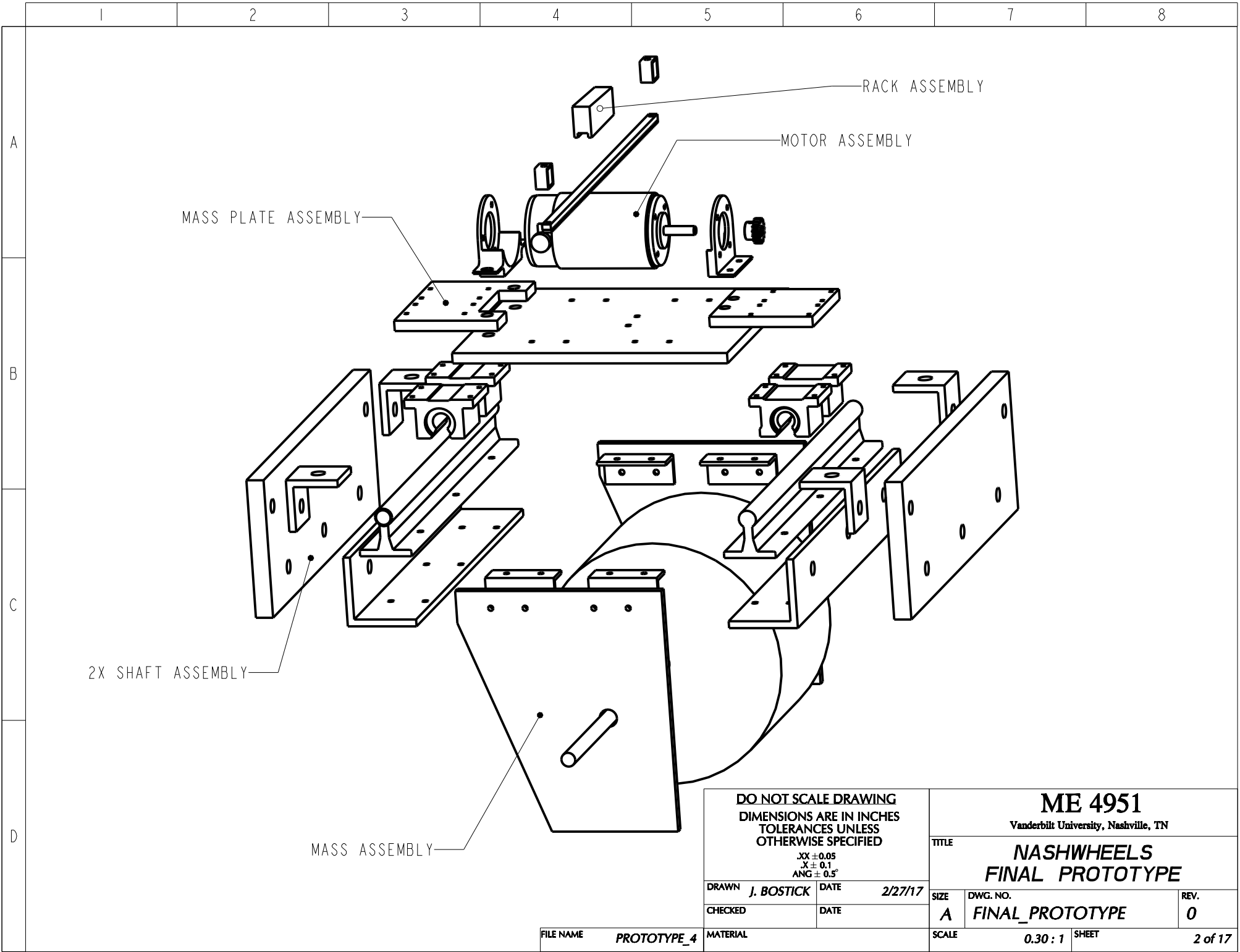


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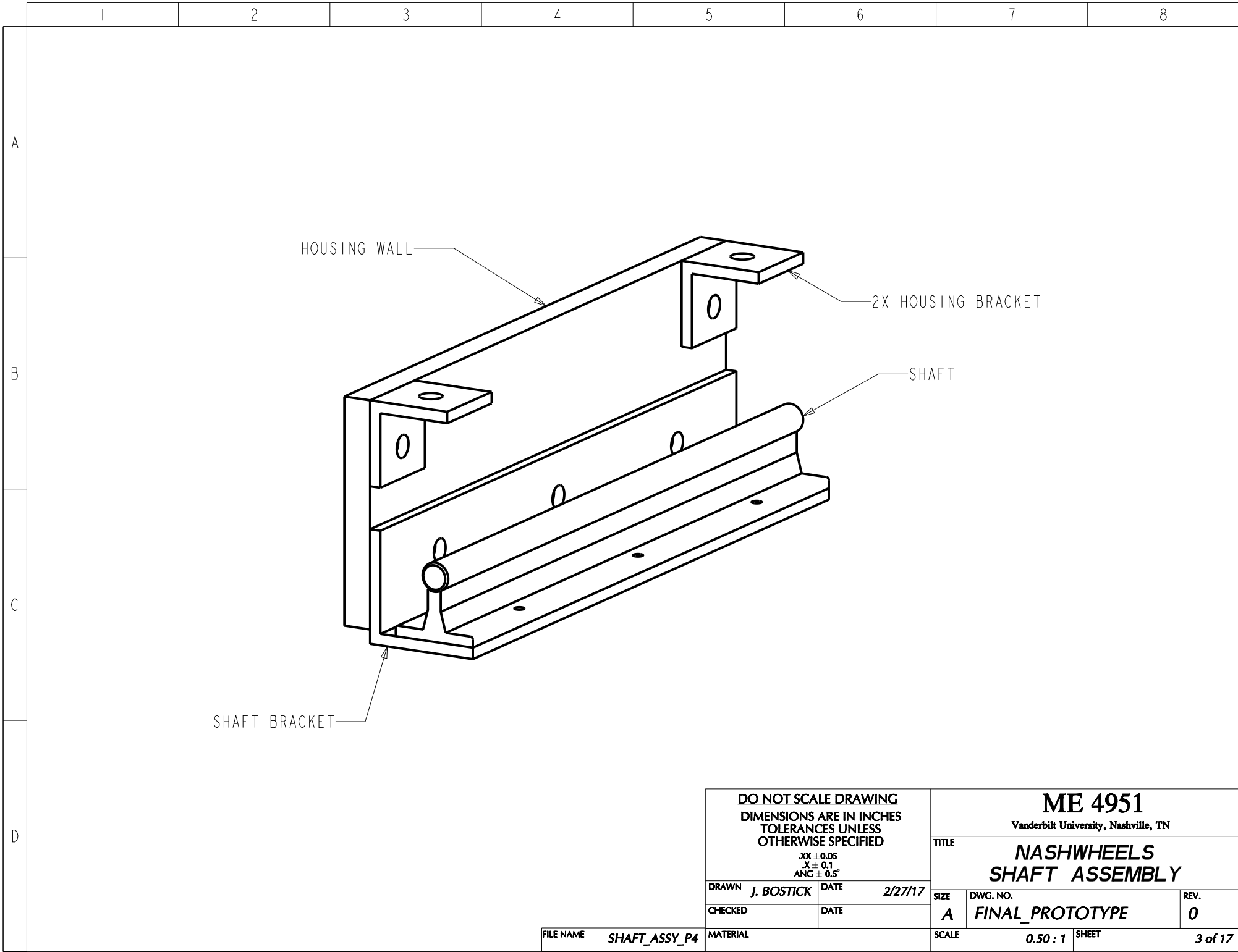
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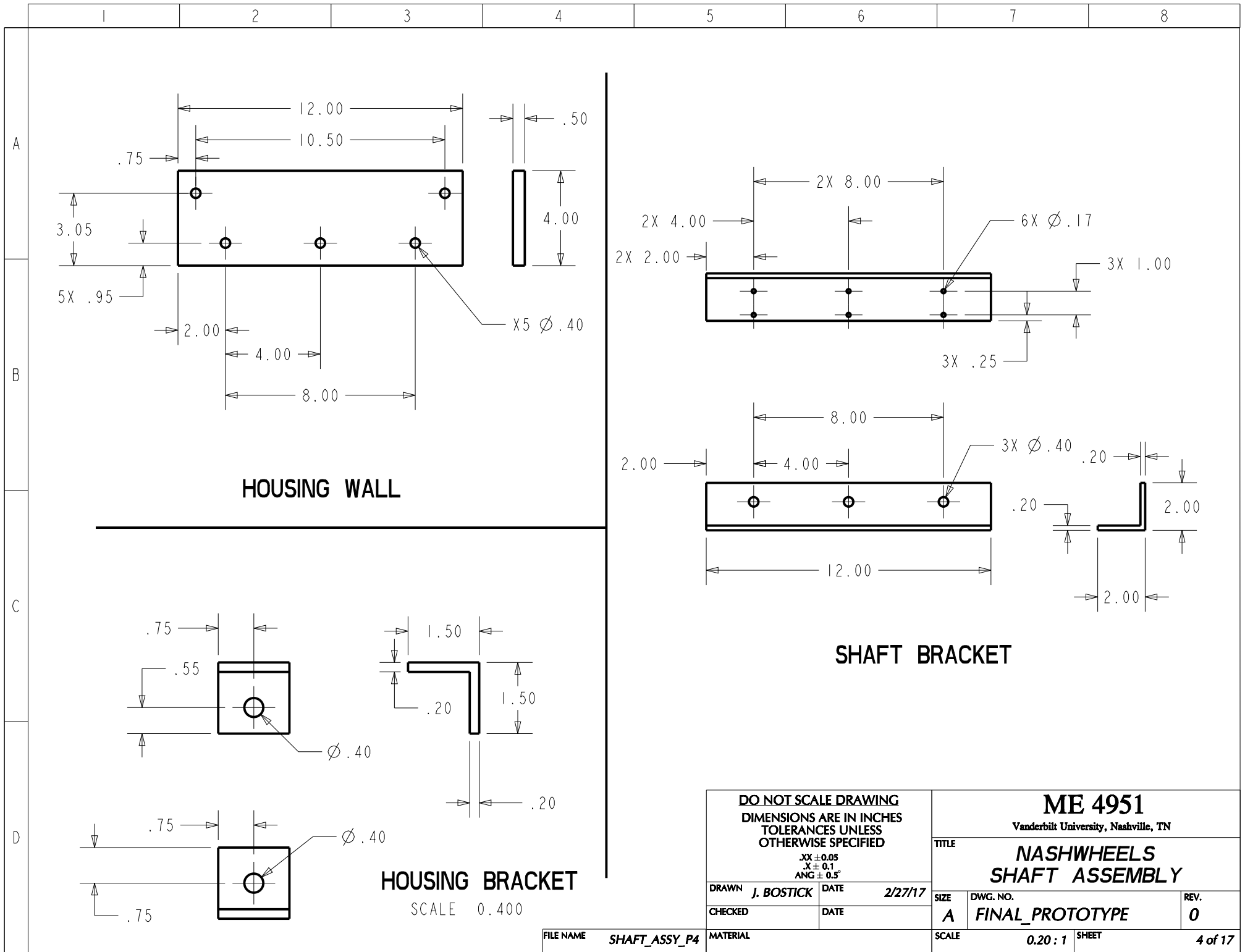


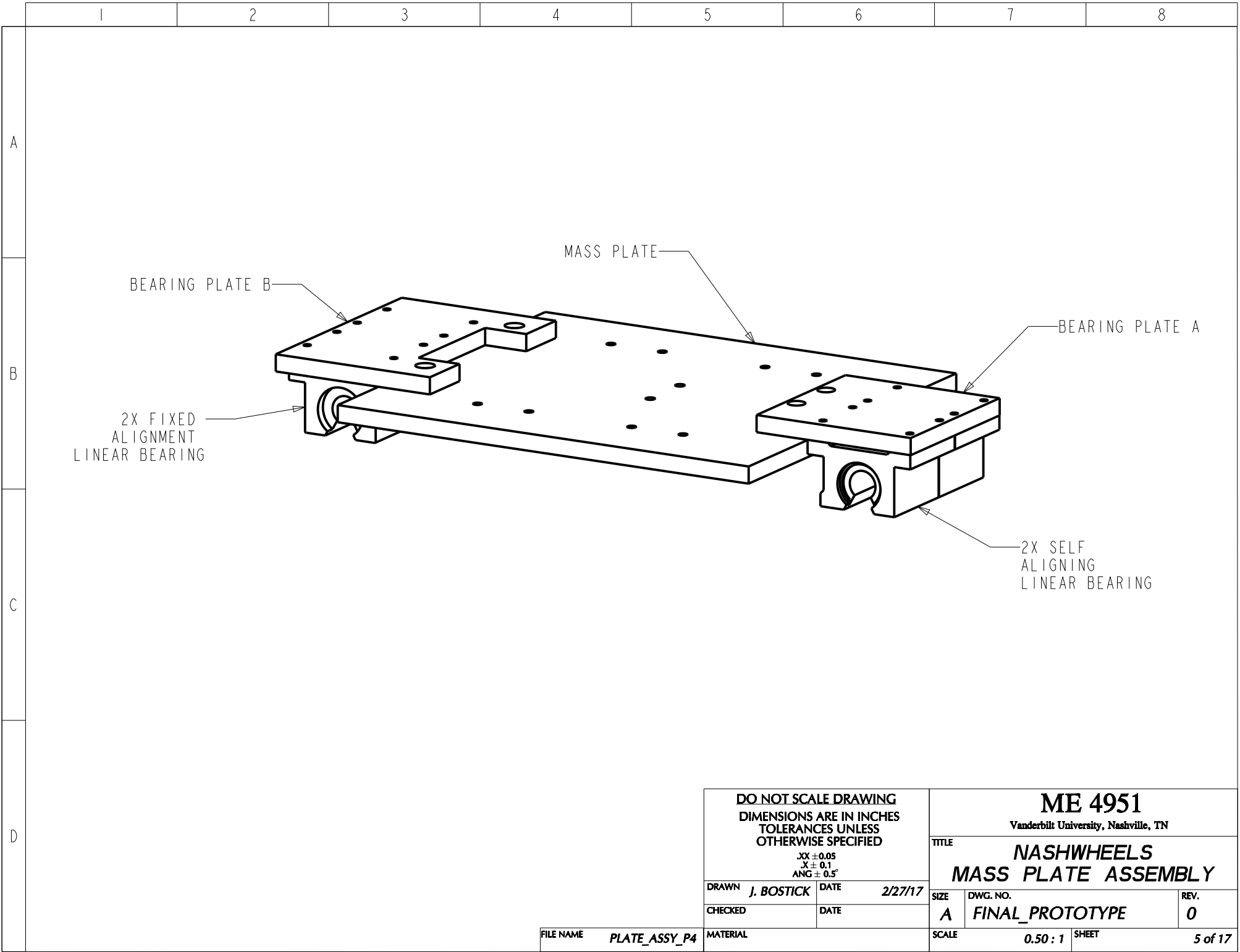
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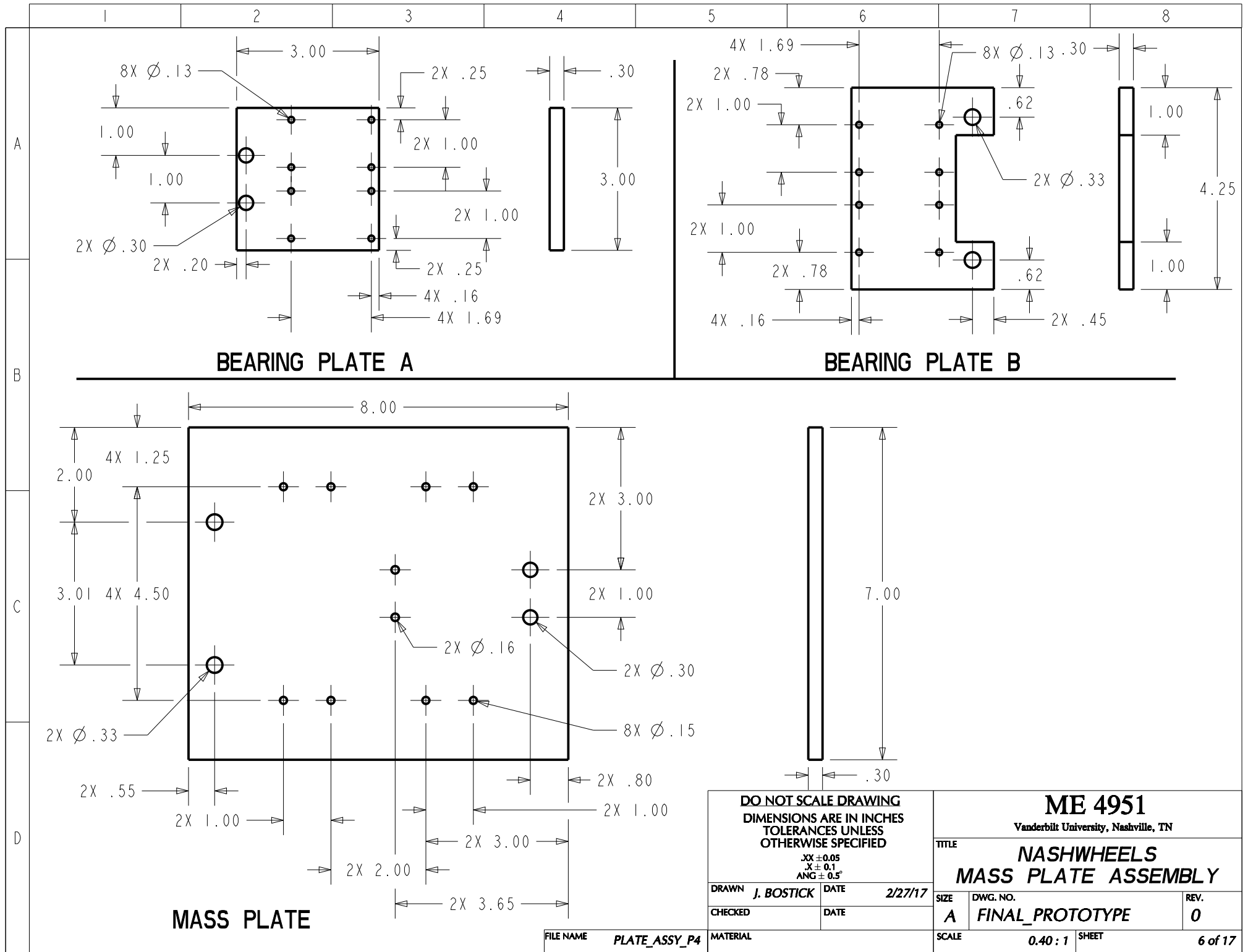




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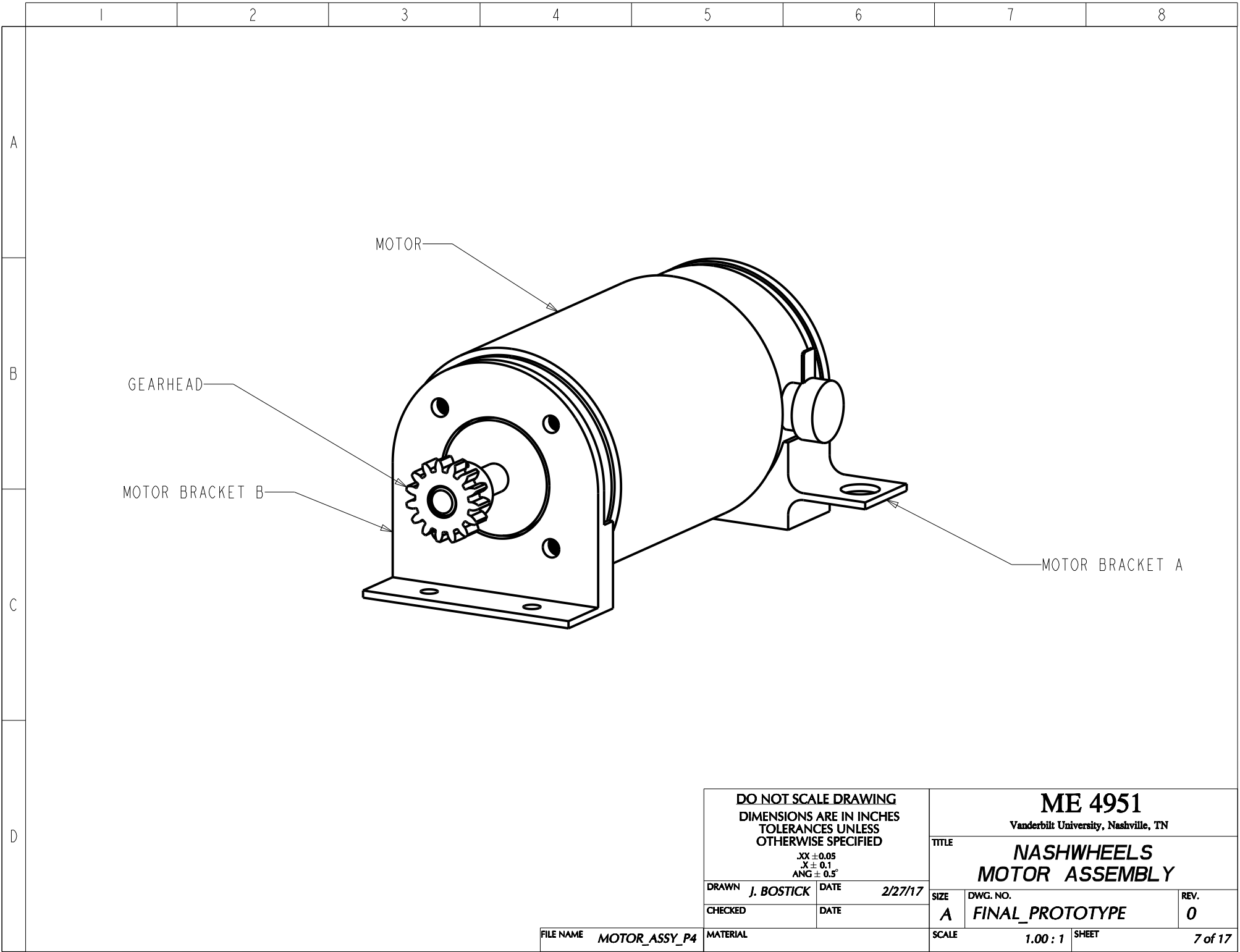
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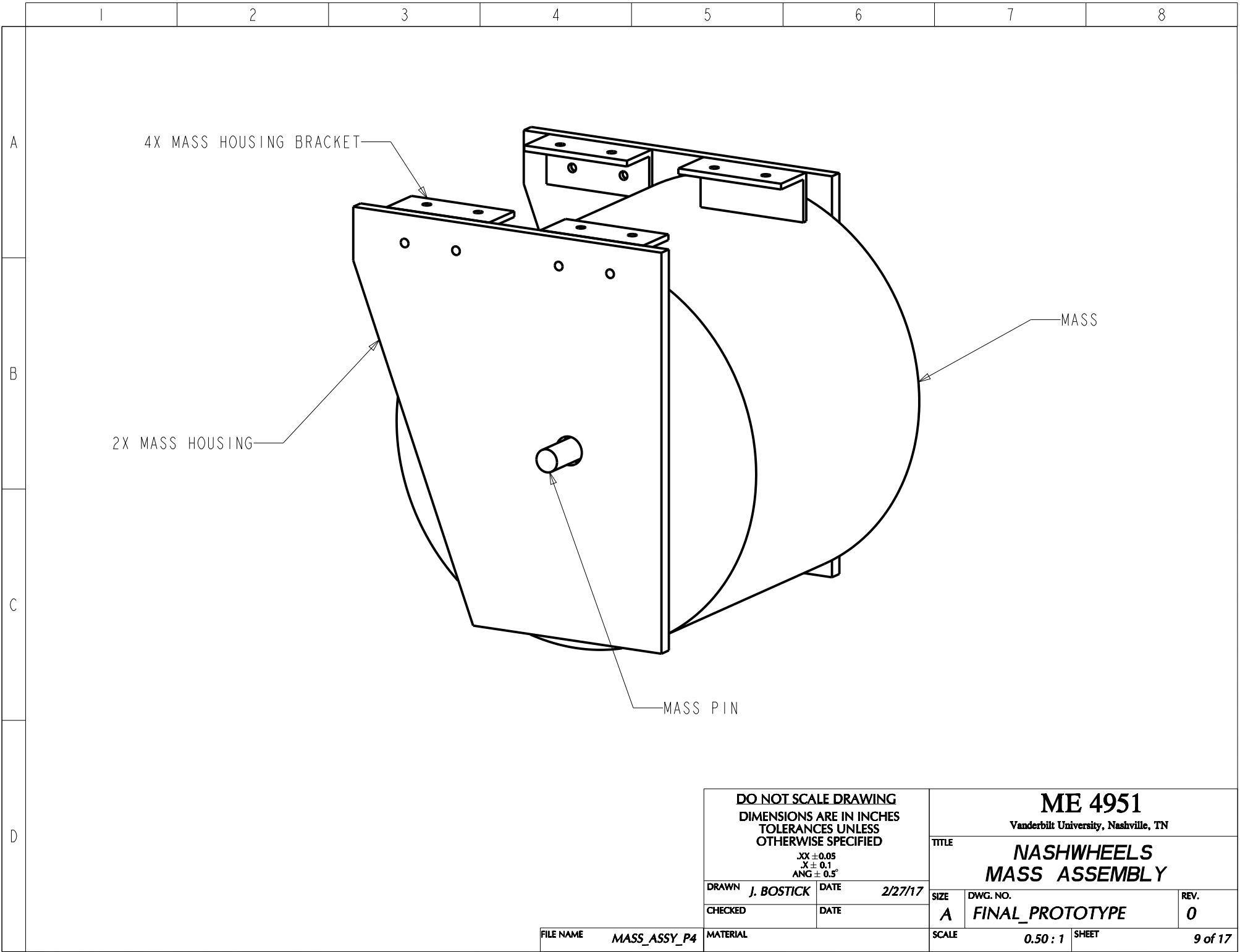
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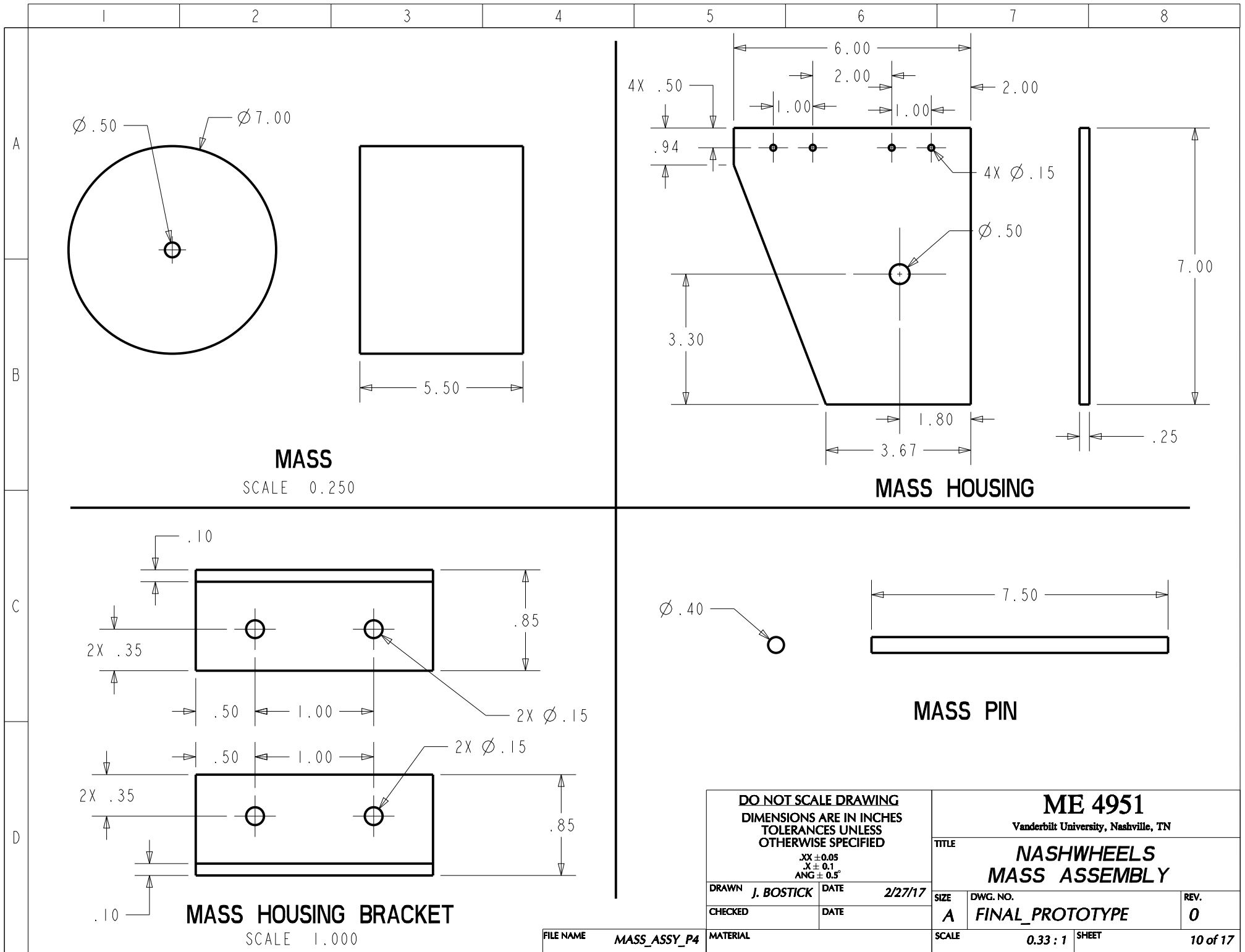


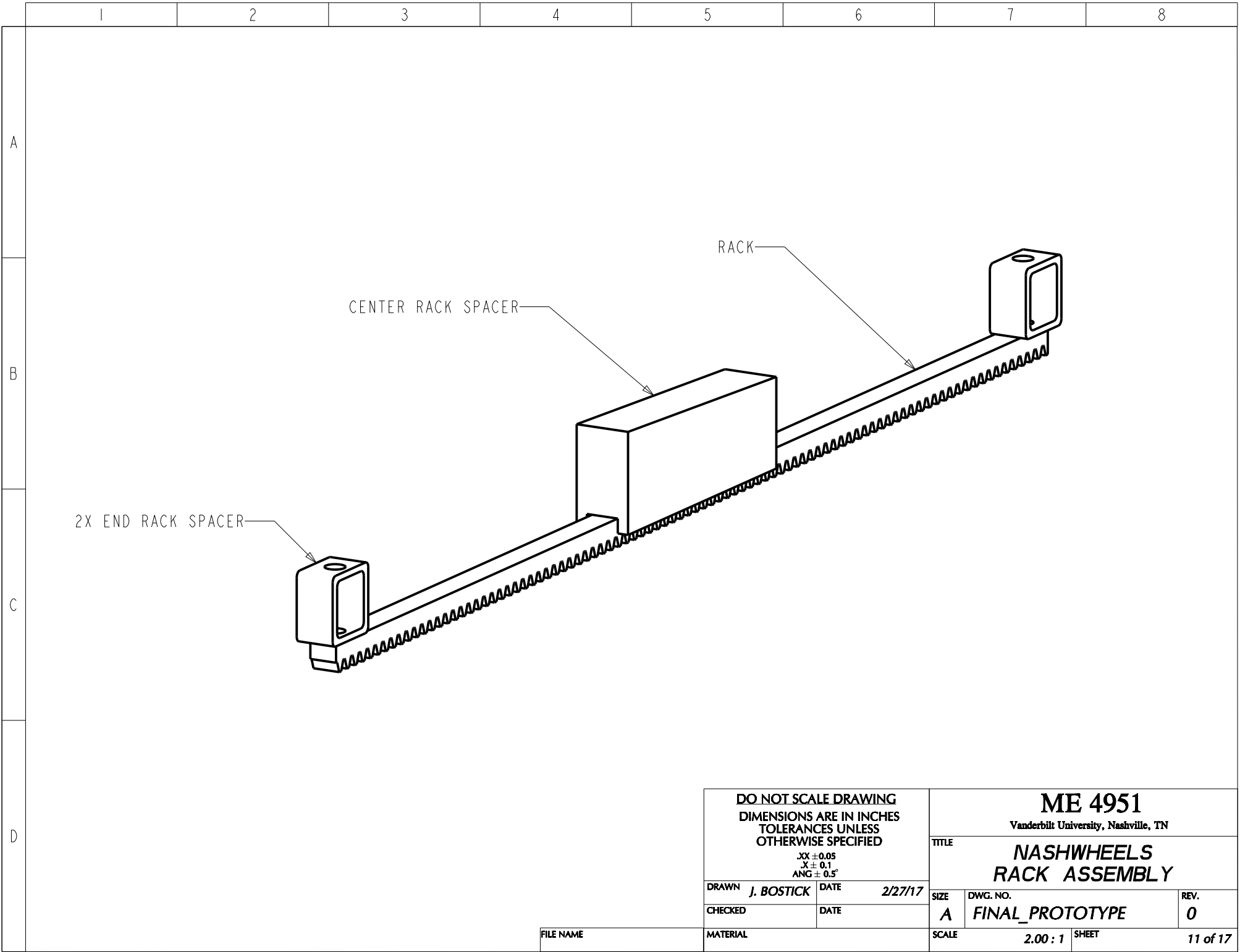
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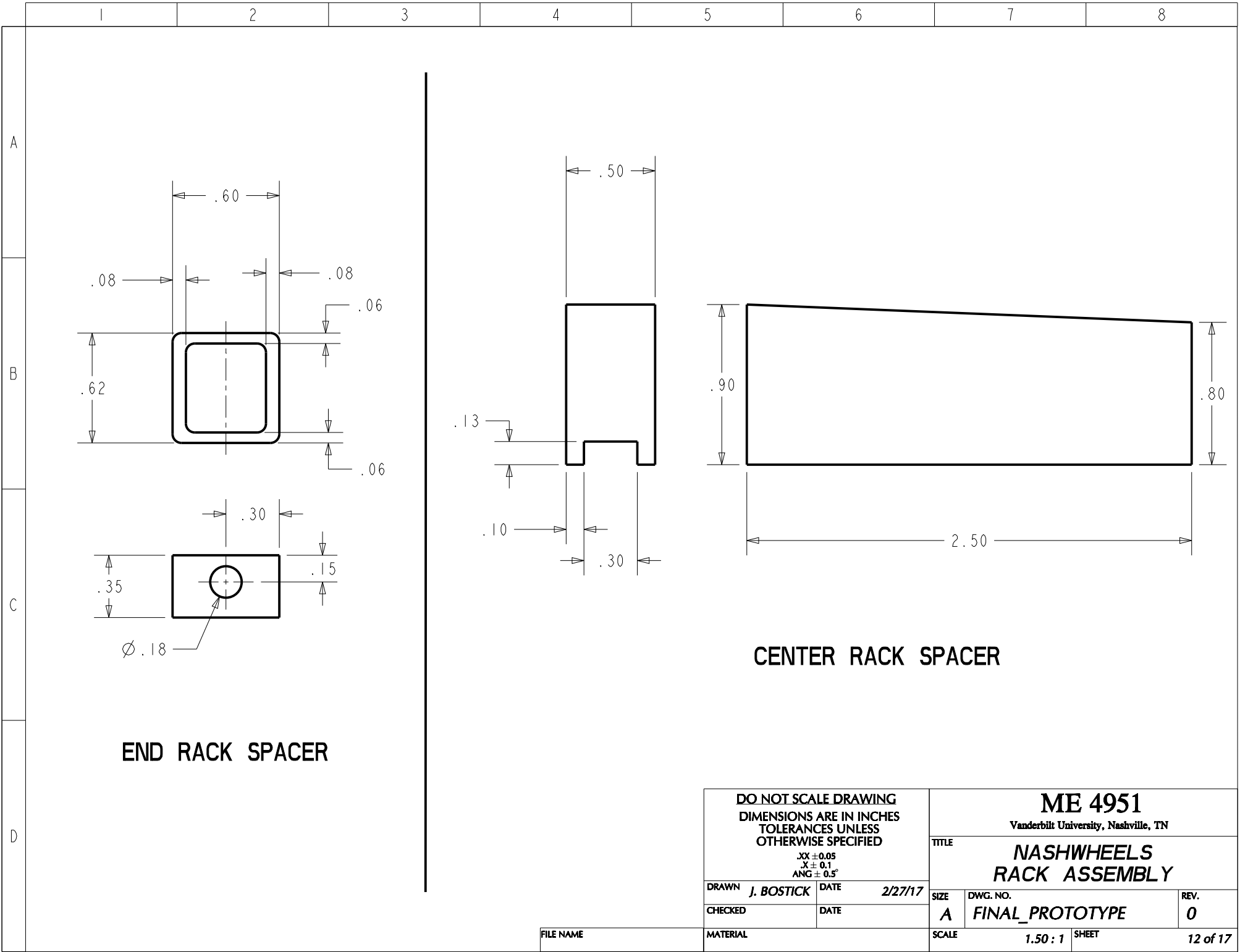
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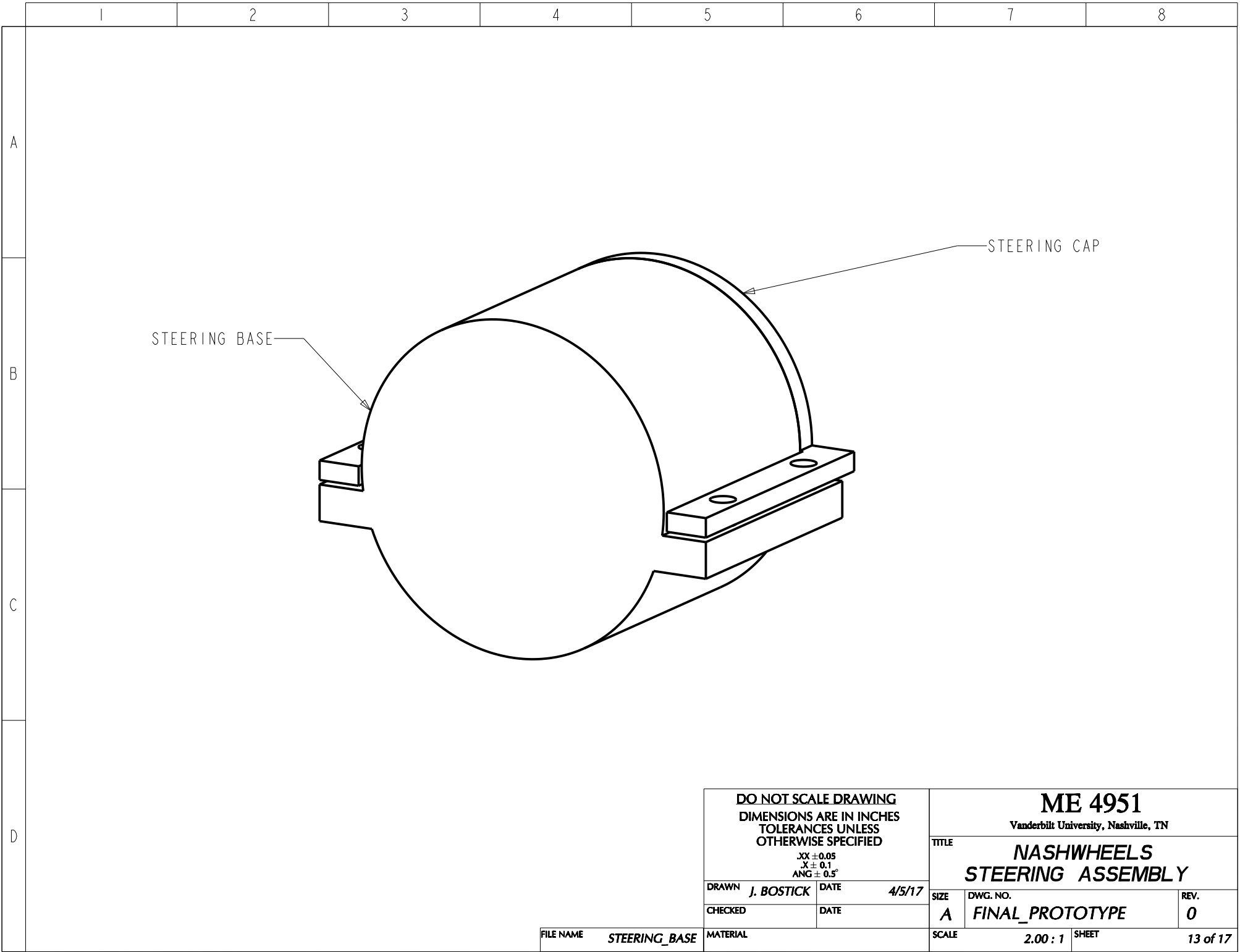






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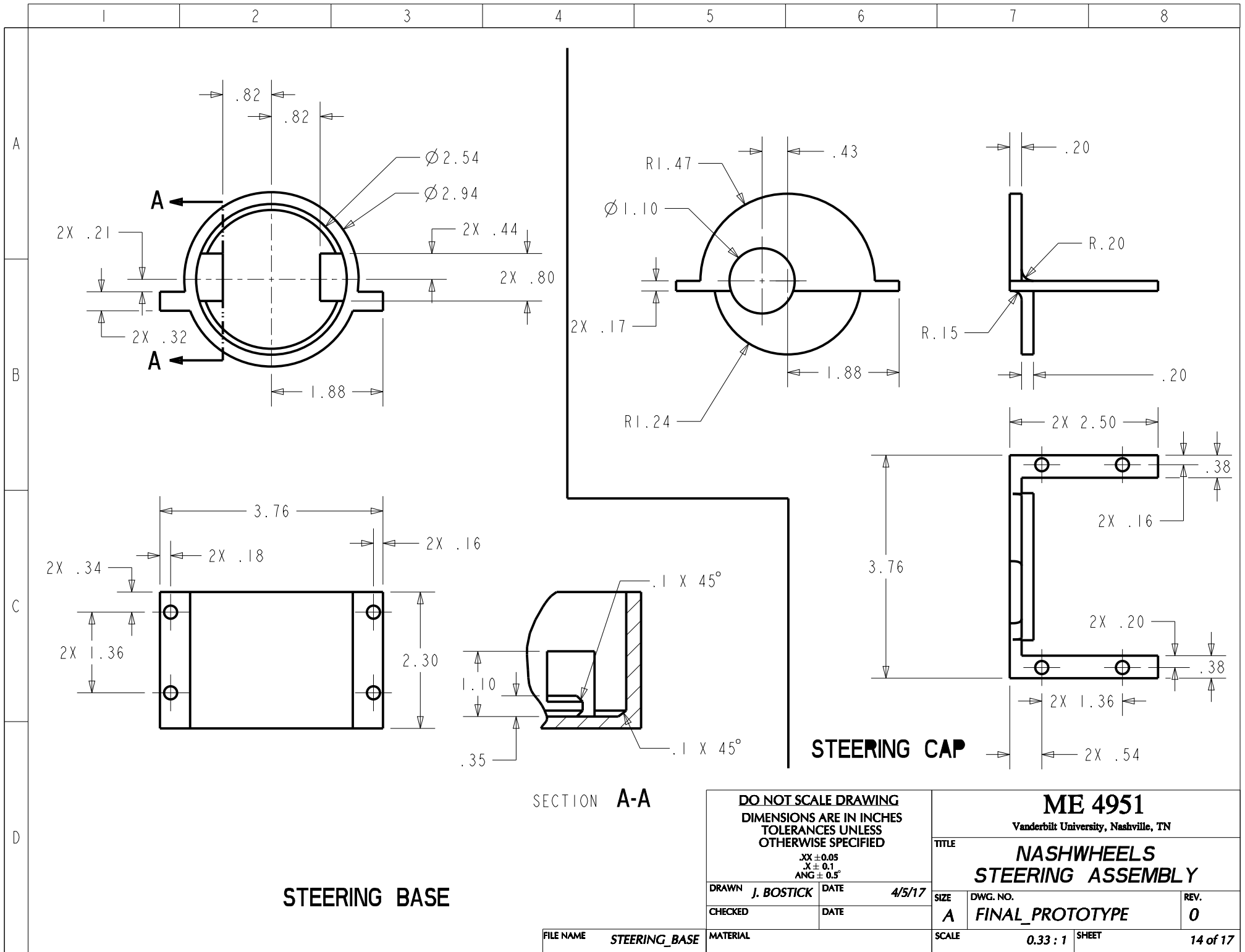


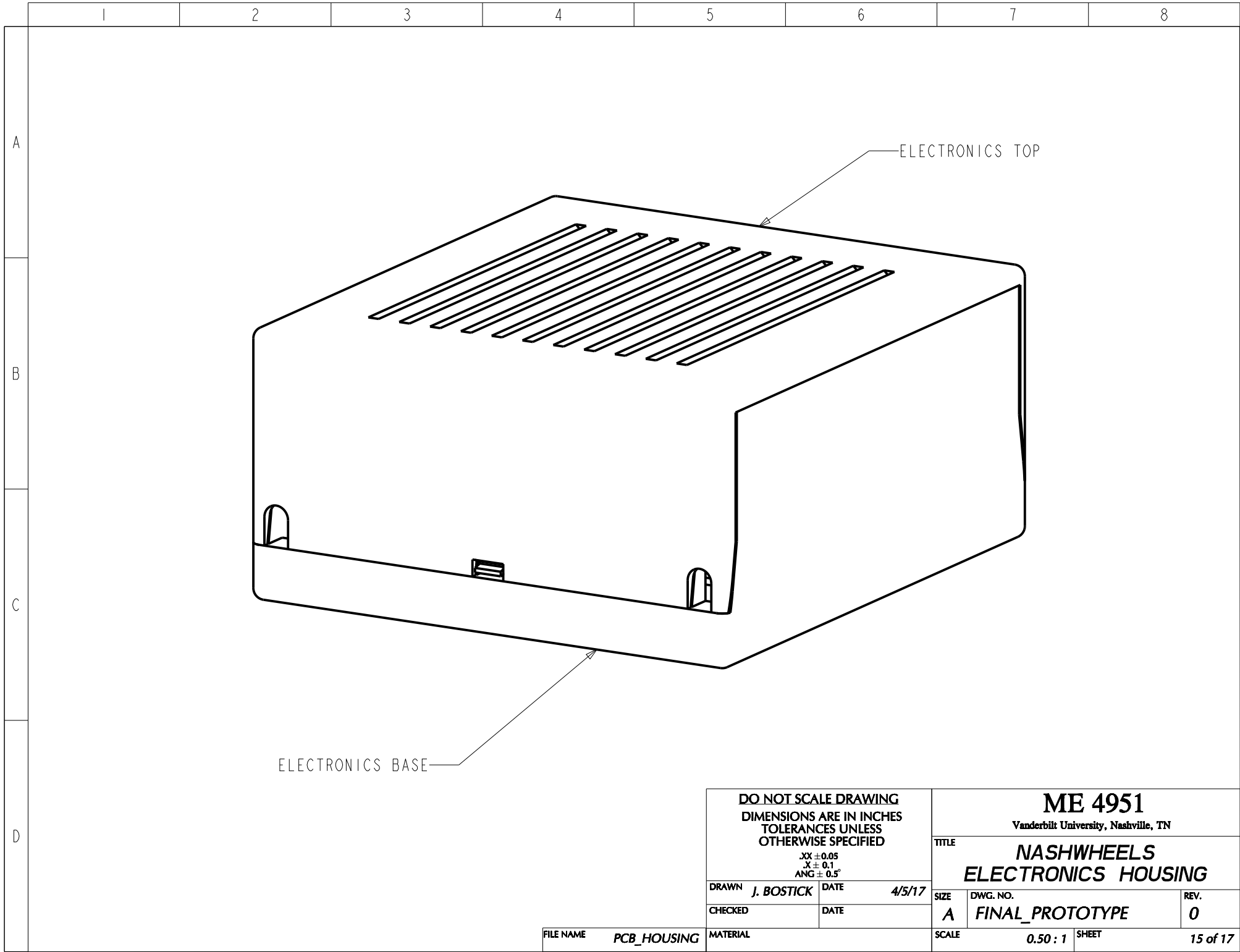
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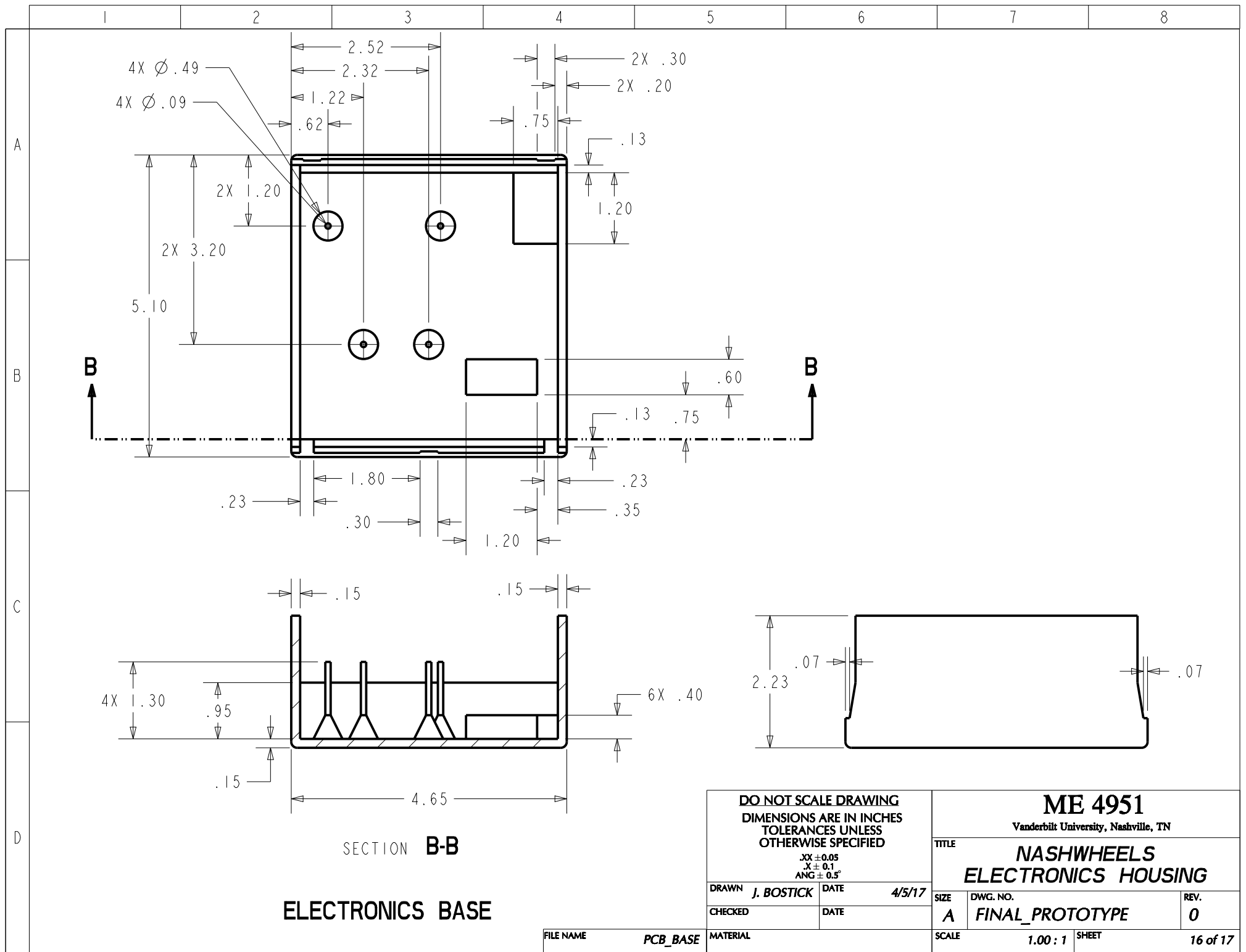


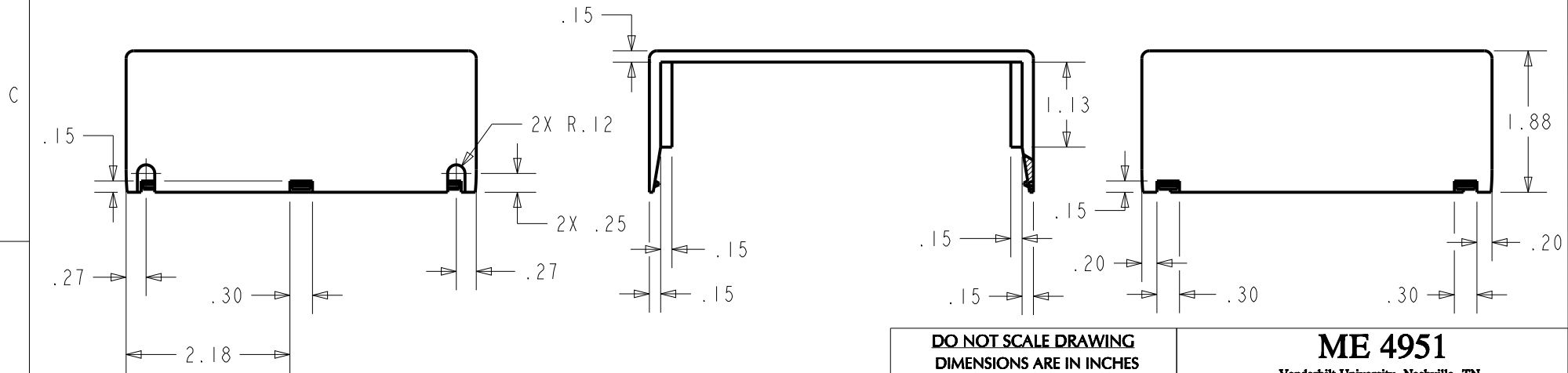
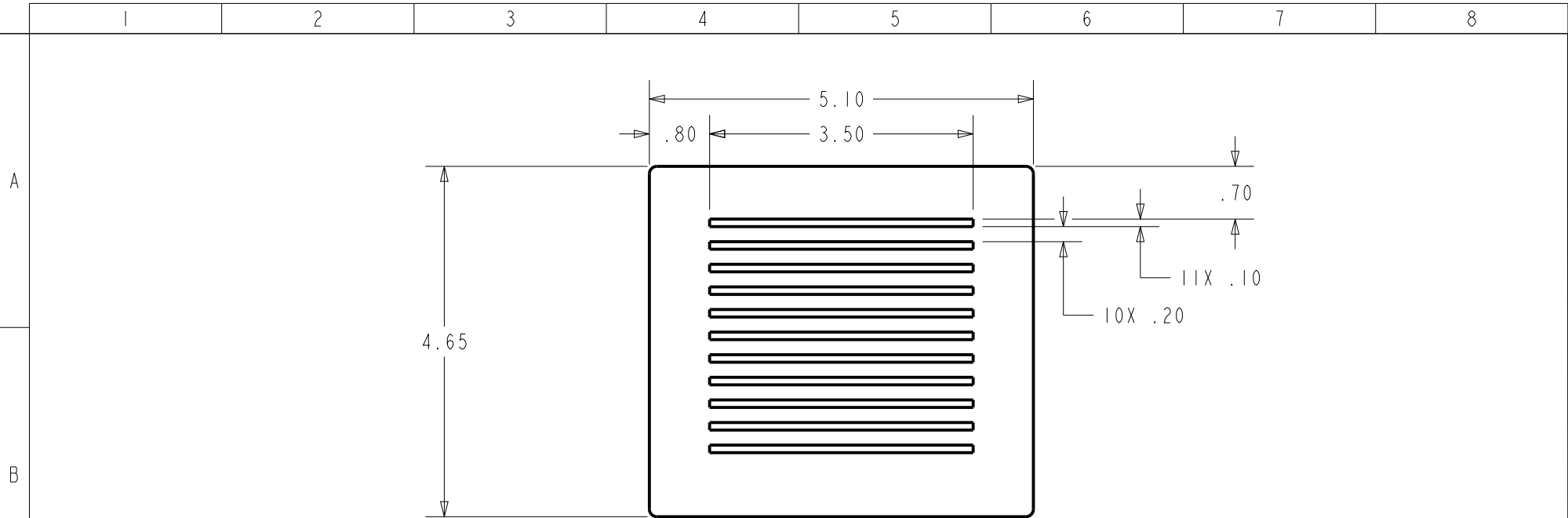
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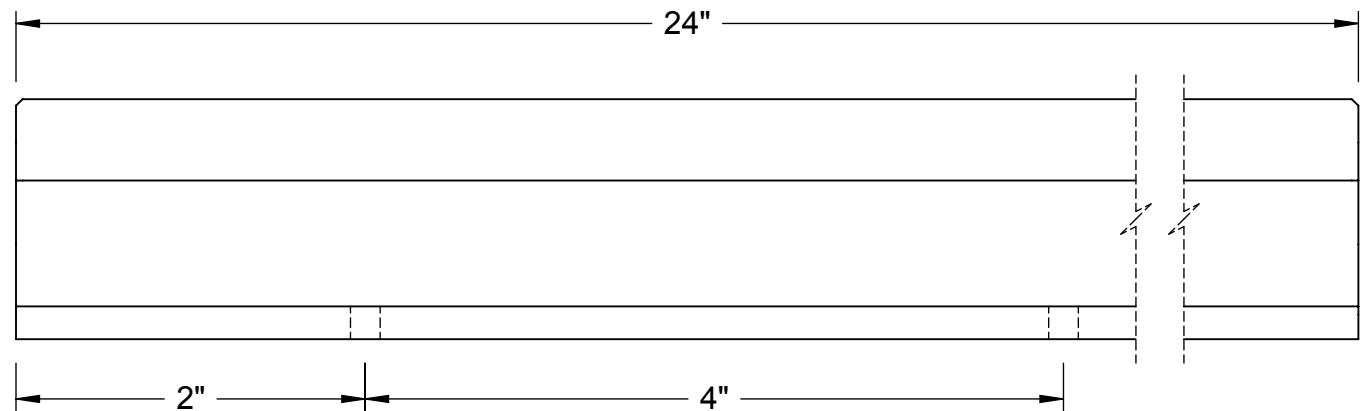
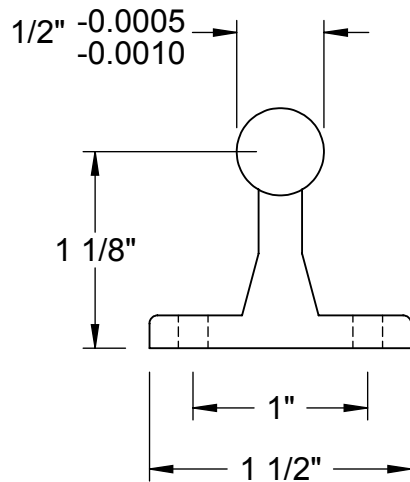
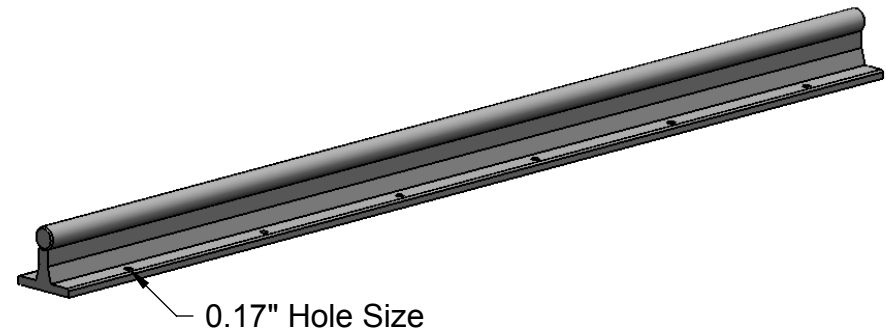
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Straightness Tolerance is 0.001" per Foot

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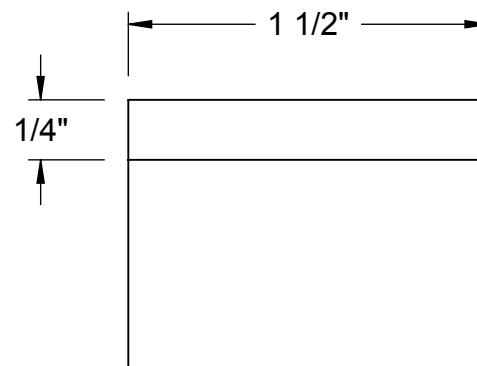
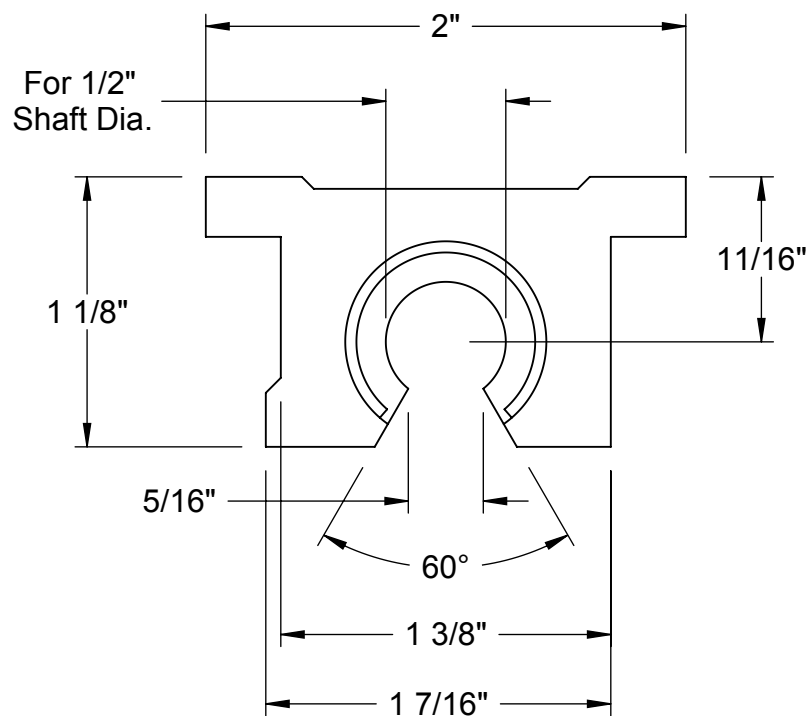
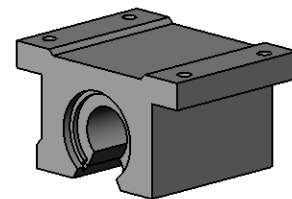
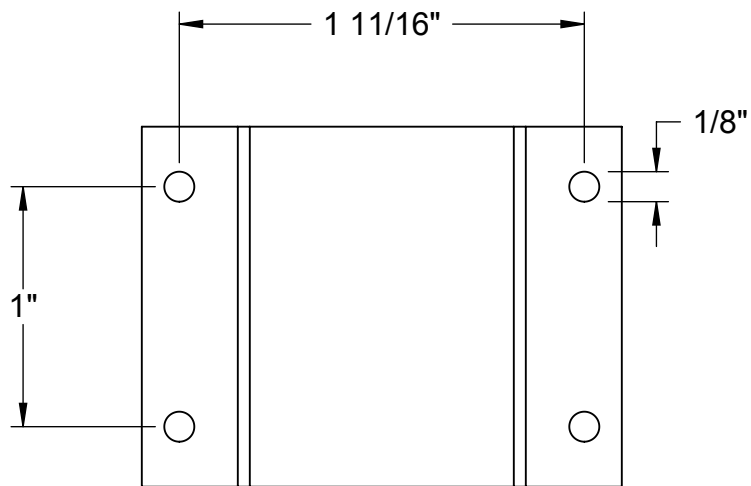
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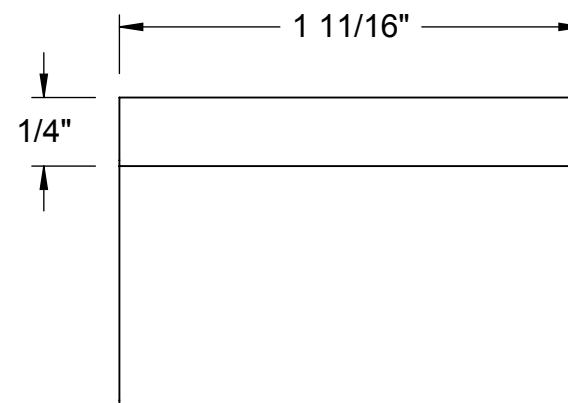
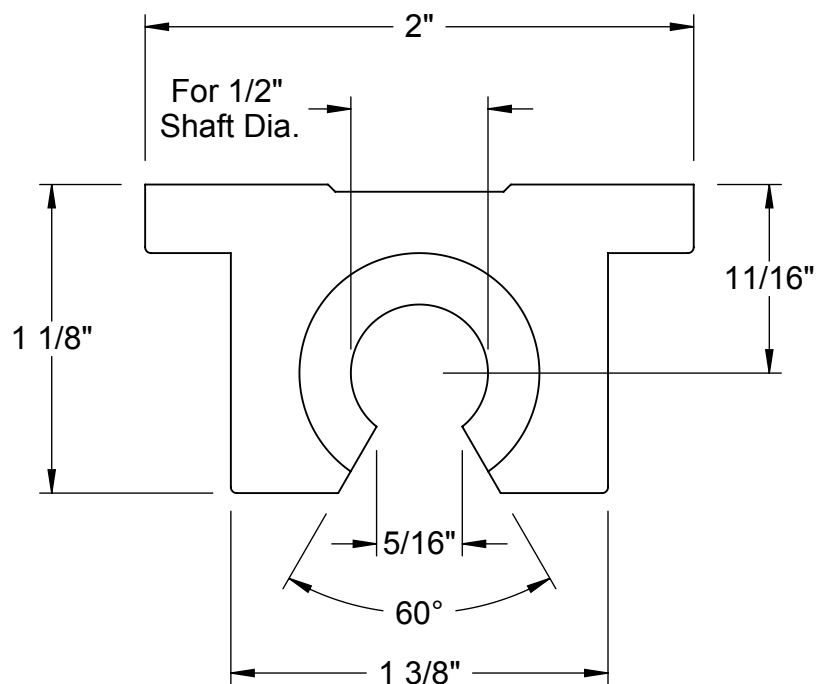
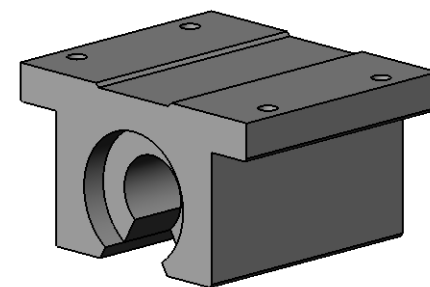
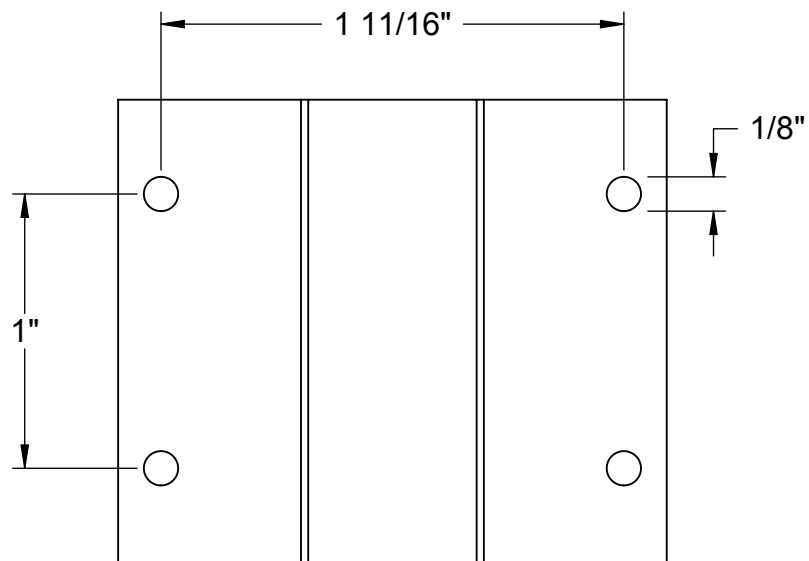
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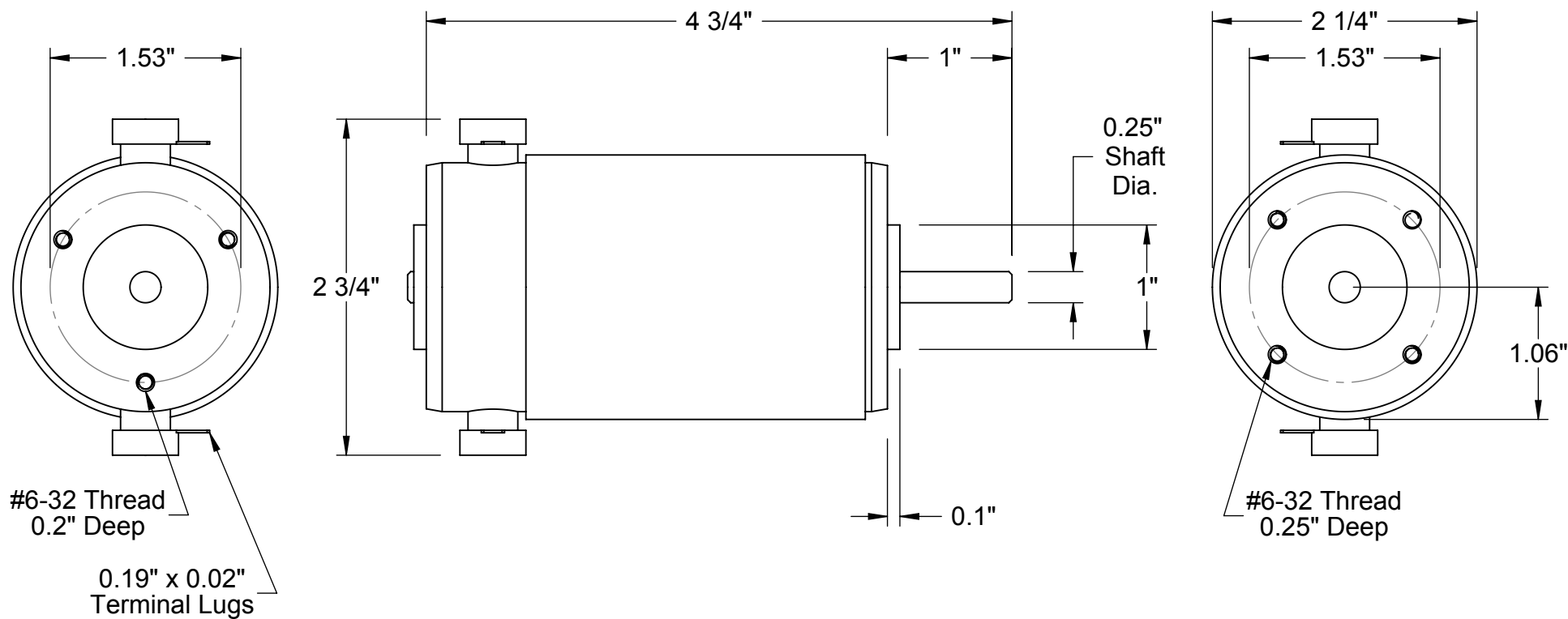
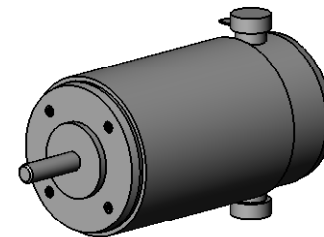
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	Self-Lubricating Pillow-Block Linear Sleeve Bearing



0.001" Shaft Clearance

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http://www.mcmaster.com © 2015 McMaster-Carr Supply Company Information in this drawing is provided for reference only.	Self-Lubricating Pillow-Block Linear Sleeve Bearing



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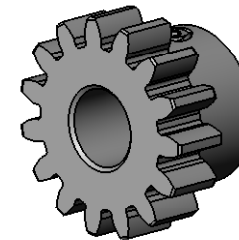
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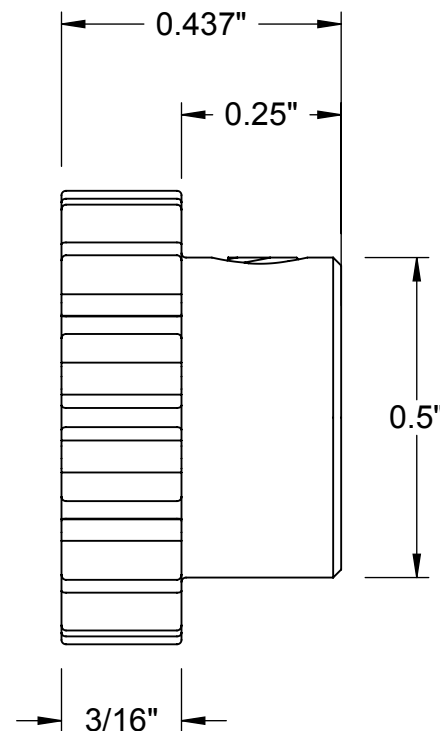
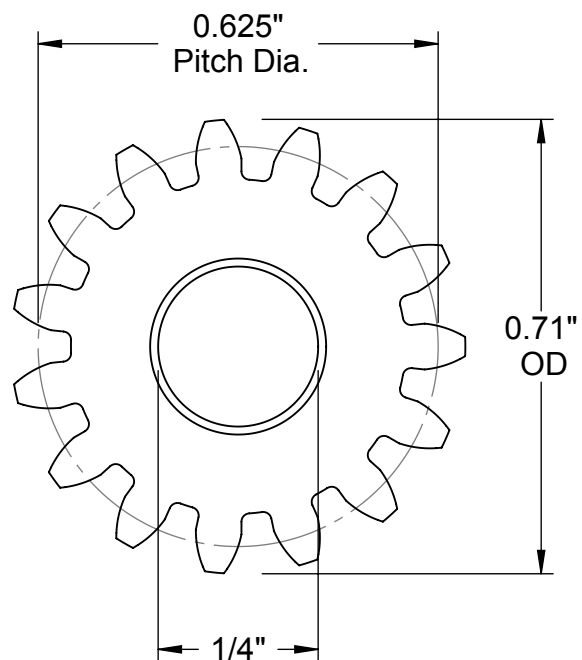
PART
NUMBER

6331K13

Compact
DC Motor



Pitch: 24
Number of Teeth: 15



McMASTER-CARR CAD

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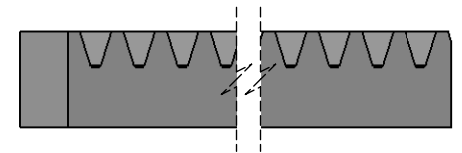
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Information in this drawing is provided for reference only.

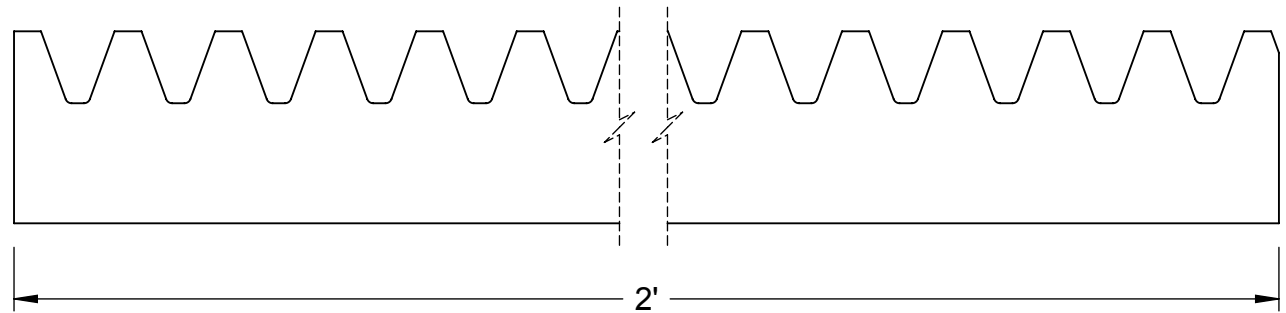
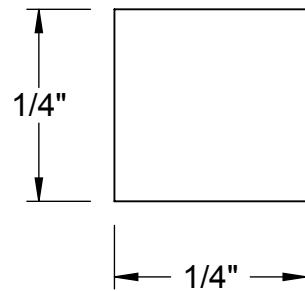
PART
NUMBER

6832K59

Corrosion-Resistant High-Load
Metal Gear - 20° Pressure Angle



Pitch: 24



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PART
NUMBER

7854K15

High-Load Metal Gear Rack - 20°
Pressure Angle



APPENDIX C: Data Sheets



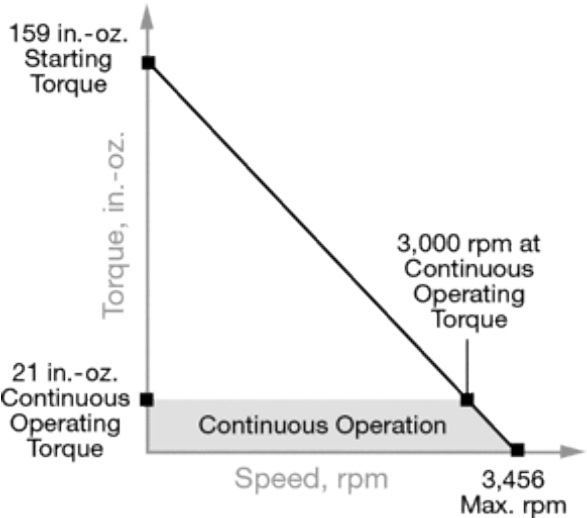
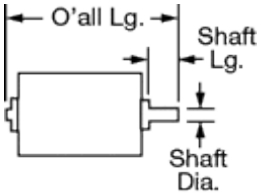
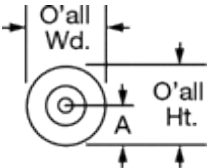
Compact Round-Face DC Motor

12V DC, 3000 rpm @ 21 in.-oz.

In stock

\$99.53 Each

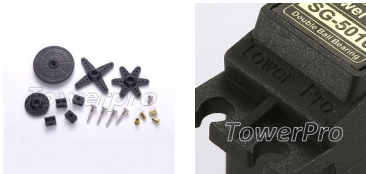
6331K13



rpm @ Continuous Operating Torque	3,000 rpm @ 21 in.-oz.
Starting Torque	159 in.-oz.
Maximum rpm	3,456
hp	0.06
DC Voltage [Nom]	12 Volts DC
Amps @ Full Load	4.9
Electrical Connection	Lug Terminals
Lug Terminals	
Width	0.187"
Thickness	0.02"
Motor Type	Brushed Permanent Magnet
Service Factor	1
Efficiency	68%
Enclosure Type	TENV
Enclosure Material	Steel
Bearing Type	Ball
Overall	
Length	4 3/4"
Width	2 1/4"
Height	2 3/4"
Shaft	
Diameter	0.250"
Length	1"
Center to Base (A)	1.06"
Mounting Orientation	Any Angle
Mounting Holes	
Thread Size	6-32
Quantity	4
Bolt Circle Diameter	1.53"
Insulation	
Class	F
Maximum Temperature	311° F

Power small machinery in spaces where other motors won't fit. Motors are rated for continuous duty. You can wire for clockwise or counterclockwise shaft rotation; instructions

Home / Servos & Parts / Standard Servo 31-49g / SG5010



SG5010

\$ 4.99

SG5010 digital servo
SG5010 is the best value of standard servo.
This standard servo is used in cars, boats, or where any standar servo is called for.
We are the original manufacturer of TowerPro SG5010 servo.
There are many counterfeit servo of TowerPro from China dealer selling on eBay, Amazon and Alibaba websites.
If the suppliers removed “TowerPro” logo from the photos and tf products description, they are selling counterfeits low quality servo.
Please identify the supplier before you purchased the goods. Or our authorized dealers who provide reliable quality servos and after services.

Specifications :

Weight: 47g
Dimension: 40.6×20.5×38mm
Stall torque: 5.5kg/cm(4.8v); 6.5kg/cm(6v);
Operating speed: 0.19sec/deg (4.8v) 0.15sec/deg (6.0v)
Operating voltage: 4.8-6v
Temperature range: 0°C_ 55°C
Gear Type: nylon gear
Temperature range: 0- 55deg
Servo Plug: JR (Fits JR and Futaba)
Dead band width: 1us
servo wire length: 32cm
servo arms &screws included and fit with Futaba servo arm
It's universal “S” type connector that fits most receivers, includir Futaba, JR, Hitec ,GWS, Cirrus, Blue Bird, Blue Arrow, Corona, Berg, Spektrum.
CE &RoHS approved

1

+

-

ADD TO CART

Categories: Servos & Parts. Standard Servo 31-49g

DESCRIPTION	ADDITIONAL INFORMATION
-------------	------------------------

Product Description

Weight(g)	47g
Torque(kg)(4.8v)	5.5

Shopping Cart

No products in the cart.

Search Products

Search for:

Search Products...

Search

Product Category

Gas Engine

- 4-Stroke Gas Engine
 - 70cc Gas Engine
 - 70cc Gas Engine Parts
- 2-Stroke Gas Engine
 - 33cc Gas Engine
 - 33cc Gas Engine Parts
 - 60cc Gas Engine
 - 60cc Gas Engine Parts
 - 120cc Gas Engine
 - 120cc Gas Engine Parts

Servos & Parts

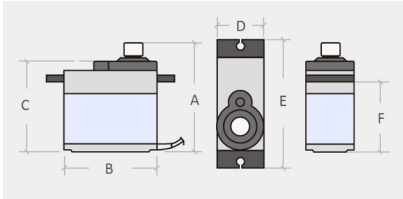
- Micro Servo 5-10g
- Mini Servo 11-20g
- Standard Servo 31-49g
- X-Large Servo 50g+
- Robotics Servo
- Servo Parts

MATAL SERVO ARM

- for Futaba
- for Hitec
- for JR

Parts & Accessories

- Propellers
 - APC Style
 - Slow Fly style
 - Sports for Gas Engine
- Voltage display



PRODUCT CONFIGURE TABLE

Speed(sec/60deg)	0.2
A(mm)	44.1
B(mm)	40.7
C(mm)	38
D(mm)	20
E(mm)	55
F(mm)	27.8

Product description

show up to 2 reviews by default

Potting material: epoxy sealed

Input voltage: DC 36V/48V(30-60V)

Output voltage: 12V

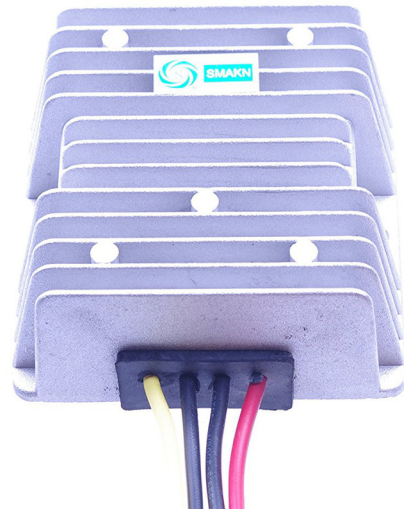
Output Current: 15A

Output Power: 180W

Conversion efficiency: Max 90%

No-load consumption: 10-12mA

Working temperature: Industrial-grade (-40 °C to +85 °C)



Used in vehicles, security systems, telecommunications, medical equipments, instruments etc Features:

Cable length: 120mm

Over-current protection

Over-temperature protection

Short-circuit protection

Input Reverse Polarity Protection: None (Please Series diode at the input port.)

Waterproof full-potting

Waterproof, seismic, damp-proof

Suitable for all kinds of harsh environments

size: 74x74x32mm/2.9x2.9x1.26 inches

Package Includes:

1x DC/DC Converter

Product information

Product Dimensions	7.4 x 5.4 x 1.7 inches
Item Weight	8.8 ounces
Shipping Weight	8.8 ounces (View shipping rates and policies)
Manufacturer	SMAKN
ASIN	B00NYK986A
Customer Reviews	4.6 out of 5 stars 2 customer reviews 4.6 out of 5 stars
Best Sellers Rank	#751 in Automotive > Tools & Equipment > Garage & Shop > Power Converters
Date first available at Amazon.com	December 18, 2014

FQP27P06

60V P-Channel MOSFET

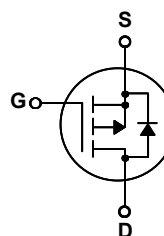
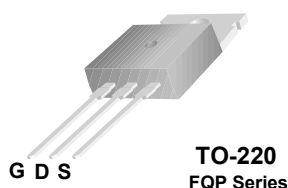
General Description

These P-Channel enhancement mode power field effect transistors are produced using Fairchild's proprietary, planar stripe, DMOS technology.

This advanced technology has been especially tailored to minimize on-state resistance, provide superior switching performance, and withstand a high energy pulse in the avalanche and commutation modes. These devices are well suited for low voltage applications such as automotive, DC/DC converters, and high efficiency switching for power management in portable and battery operated products.

Features

- -27A, -60V, $R_{DS(on)} = 0.07\Omega @ V_{GS} = -10V$
- Low gate charge (typical 33 nC)
- Low C_{rss} (typical 120 pF)
- Fast switching
- 100% avalanche tested
- Improved dv/dt capability
- 175°C maximum junction temperature rating



Absolute Maximum Ratings $T_C = 25^\circ\text{C}$ unless otherwise noted

Symbol	Parameter	FQP27P06	Units
V_{DSS}	Drain-Source Voltage	-60	V
I_D	Drain Current - Continuous ($T_C = 25^\circ\text{C}$) - Continuous ($T_C = 100^\circ\text{C}$)	-27	A
		-19.1	A
I_{DM}	Drain Current - Pulsed (Note 1)	-108	A
V_{GSS}	Gate-Source Voltage	± 25	V
E_{AS}	Single Pulsed Avalanche Energy (Note 2)	560	mJ
I_{AR}	Avalanche Current (Note 1)	-27	A
E_{AR}	Repetitive Avalanche Energy (Note 1)	12	mJ
dv/dt	Peak Diode Recovery dv/dt (Note 3)	-7.0	V/ns
P_D	Power Dissipation ($T_C = 25^\circ\text{C}$) - Derate above 25°C	120	W
		0.8	W/°C
T_J, T_{STG}	Operating and Storage Temperature Range	-55 to +175	°C
T_L	Maximum lead temperature for soldering purposes, 1/8" from case for 5 seconds	300	°C

Thermal Characteristics

Symbol	Parameter	Typ	Max	Units
$R_{\theta JC}$	Thermal Resistance, Junction-to-Case	--	1.25	°C/W
$R_{\theta CS}$	Thermal Resistance, Case-to-Sink	0.5	--	°C/W
$R_{\theta JA}$	Thermal Resistance, Junction-to-Ambient	--	62.5	°C/W

Electrical Characteristics $T_C = 25^\circ\text{C}$ unless otherwise noted

Symbol	Parameter	Test Conditions	Min	Typ	Max	Units
Off Characteristics						
BV_{DSS}	Drain-Source Breakdown Voltage	$V_{GS} = 0\text{ V}, I_D = -250\text{ }\mu\text{A}$	-60	--	--	V
$\Delta BV_{DSS} / \Delta T_J$	Breakdown Voltage Temperature Coefficient	$I_D = -250\text{ }\mu\text{A}$, Referenced to 25°C	--	-0.06	--	V/ $^\circ\text{C}$
I_{DSS}	Zero Gate Voltage Drain Current	$V_{DS} = -60\text{ V}, V_{GS} = 0\text{ V}$	--	--	-1	μA
		$V_{DS} = -48\text{ V}, T_C = 150^\circ\text{C}$	--	--	-10	μA
I_{GSSF}	Gate-Body Leakage Current, Forward	$V_{GS} = -25\text{ V}, V_{DS} = 0\text{ V}$	--	--	-100	nA
I_{GSSR}	Gate-Body Leakage Current, Reverse	$V_{GS} = 25\text{ V}, V_{DS} = 0\text{ V}$	--	--	100	nA

On Characteristics

$V_{GS(th)}$	Gate Threshold Voltage	$V_{DS} = V_{GS}, I_D = -250\text{ }\mu\text{A}$	-2.0	--	-4.0	V
$R_{DS(on)}$	Static Drain-Source On-Resistance	$V_{GS} = -10\text{ V}, I_D = -13.5\text{ A}$	--	0.055	0.07	Ω
g_{FS}	Forward Transconductance	$V_{DS} = -30\text{ V}, I_D = -13.5\text{ A}$ (Note 4)	--	12.4	--	S

Dynamic Characteristics

C_{iss}	Input Capacitance	$V_{DS} = -25\text{ V}, V_{GS} = 0\text{ V},$ $f = 1.0\text{ MHz}$	--	1100	1400	pF
C_{oss}	Output Capacitance		--	510	660	pF
C_{rss}	Reverse Transfer Capacitance		--	120	155	pF

Switching Characteristics

$t_{d(on)}$	Turn-On Delay Time	$V_{DD} = -30\text{ V}, I_D = -13.5\text{ A},$ $R_G = 25\text{ }\Omega$ (Note 4, 5)	--	18	45	ns
t_r	Turn-On Rise Time		--	185	380	ns
$t_{d(off)}$	Turn-Off Delay Time		--	30	70	ns
t_f	Turn-Off Fall Time		--	90	190	ns
Q_g	Total Gate Charge	$V_{DS} = -48\text{ V}, I_D = -27\text{ A},$ $V_{GS} = -10\text{ V}$ (Note 4, 5)	--	33	43	nC
Q_{gs}	Gate-Source Charge		--	6.8	--	nC
Q_{gd}	Gate-Drain Charge		--	18	--	nC

Drain-Source Diode Characteristics and Maximum Ratings

I _S	Maximum Continuous Drain-Source Diode Forward Current		--	--	-27	A
I _{SM}	Maximum Pulsed Drain-Source Diode Forward Current		--	--	-108	A
V _{SD}	Drain-Source Diode Forward Voltage	V _{GS} = 0 V, I _S = -27 A	--	--	-4.0	V
t _{rr}	Reverse Recovery Time	V _{GS} = 0 V, I _S = -27 A,	--	105	--	ns
Q _{rr}	Reverse Recovery Charge	dI _F / dt = 100 A/μs (Note 4)	--	0.41	--	μC

Notes:

1. Repetitive Rating : Pulse width limited by maximum junction temperature
2. $L = 0.9\text{ mH}$, $I_{AS} = -27\text{ A}$, $V_{DD} = -25\text{ V}$, $R_G = 25\text{ }\Omega$, Starting $T_J = 25^\circ\text{C}$
3. $I_{SD} \leq -27\text{ A}$, $dI/dt \leq 300\text{ A}/\mu\text{s}$, $V_{DD} \leq BV_{DSS}$, Starting $T_J = 25^\circ\text{C}$
4. Pulse Test : Pulse width $\leq 300\mu\text{s}$, Duty cycle $\leq 2\%$
5. Essentially independent of operating temperature

Typical Characteristics

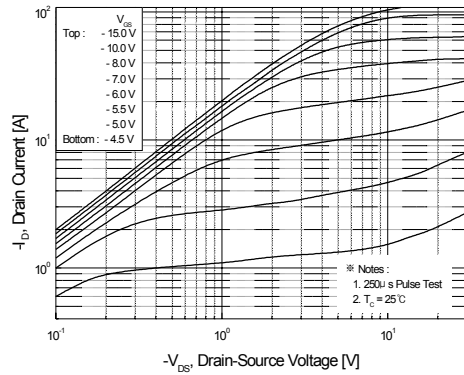


Figure 1. On-Region Characteristics

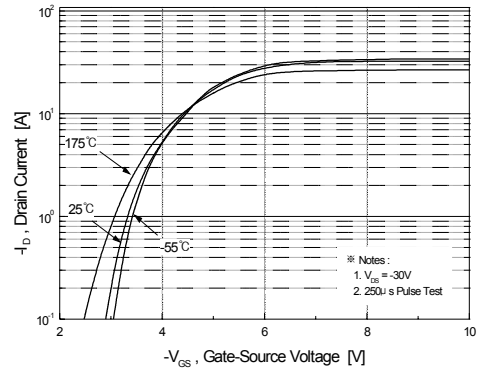


Figure 2. Transfer Characteristics

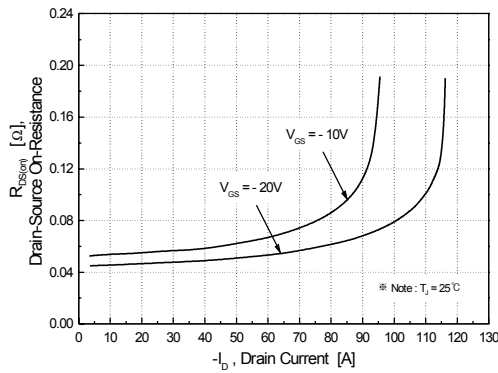


Figure 3. On-Resistance Variation vs. Drain Current and Gate Voltage

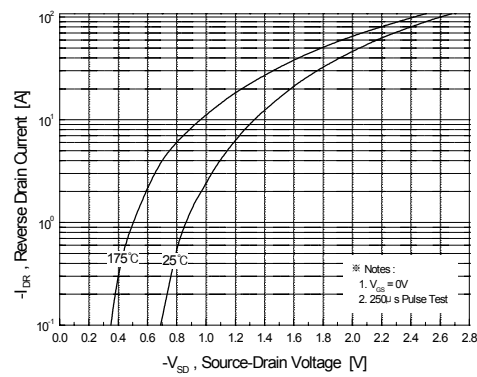


Figure 4. Body Diode Forward Voltage Variation vs. Source Current and Temperature

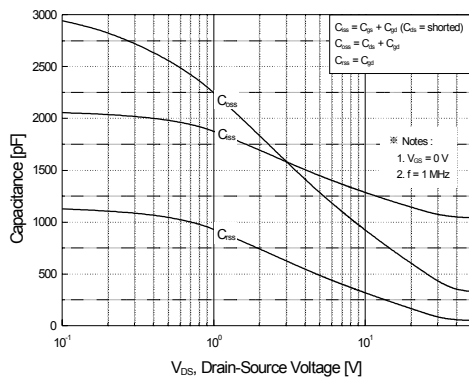


Figure 5. Capacitance Characteristics

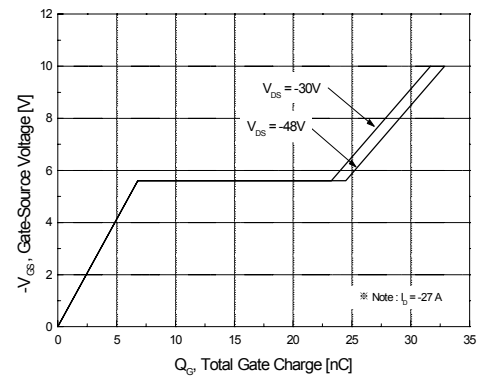


Figure 6. Gate Charge Characteristics

Typical Characteristics (Continued)

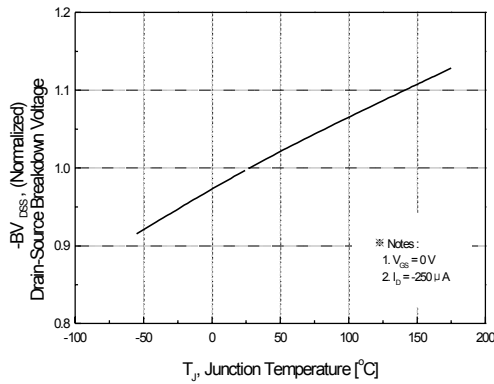


Figure 7. Breakdown Voltage Variation vs. Temperature

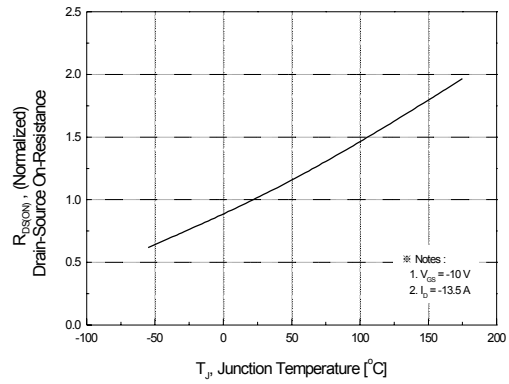


Figure 8. On-Resistance Variation vs. Temperature

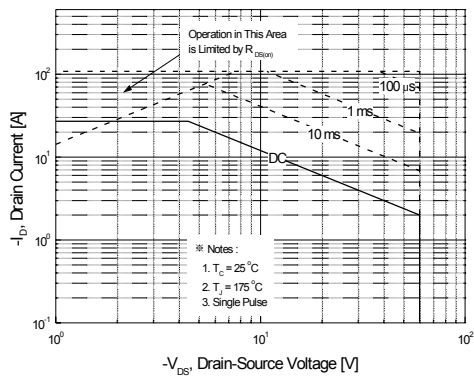


Figure 9. Maximum Safe Operating Area

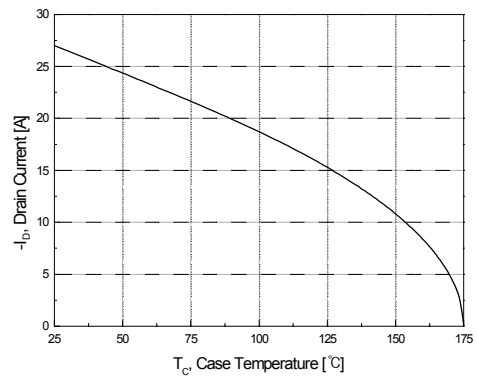


Figure 10. Maximum Drain Current vs. Case Temperature

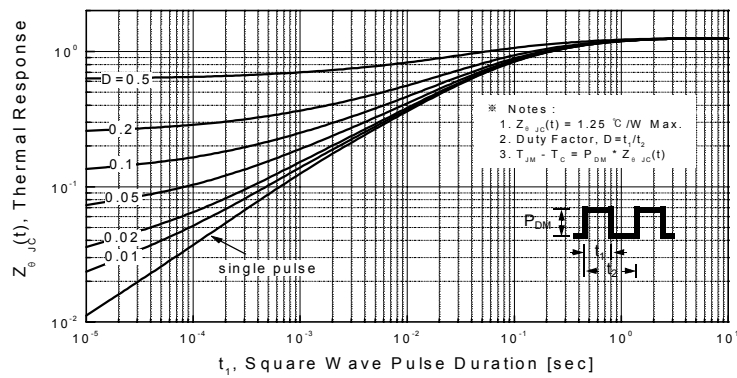
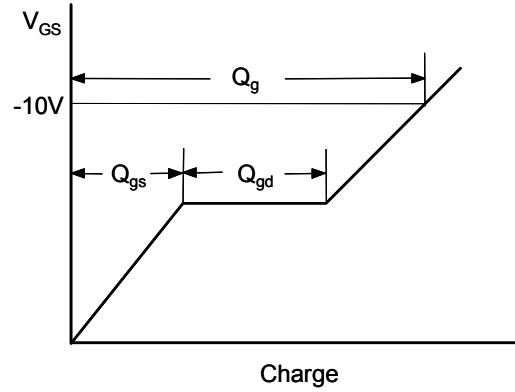
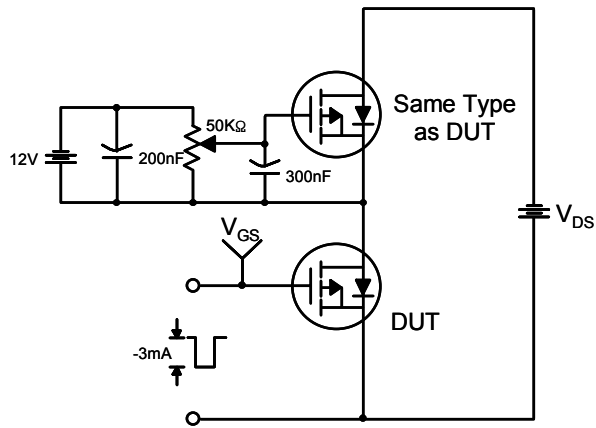
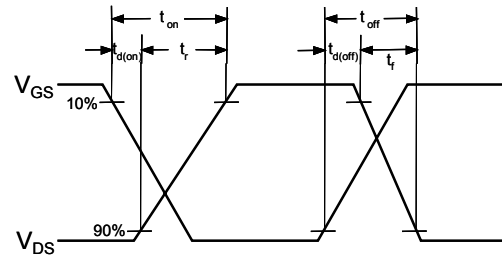
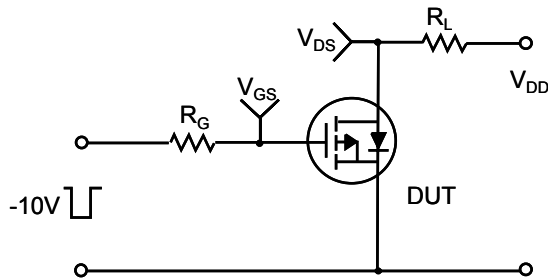


Figure 11. Transient Thermal Response Curve

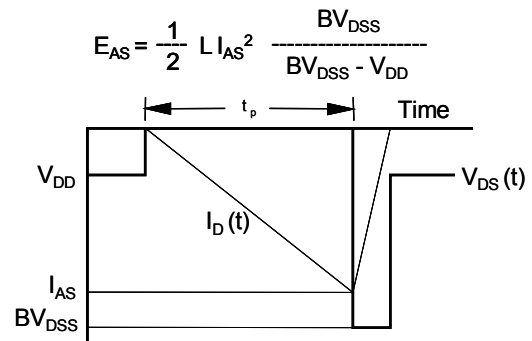
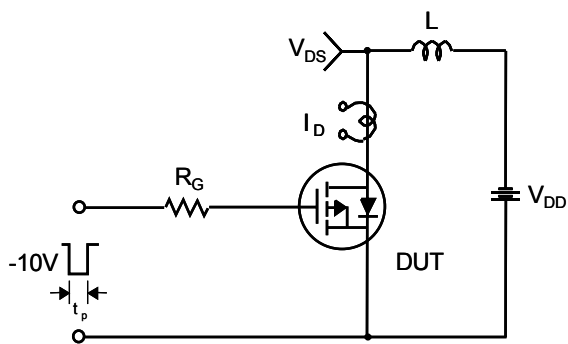
Gate Charge Test Circuit & Waveform



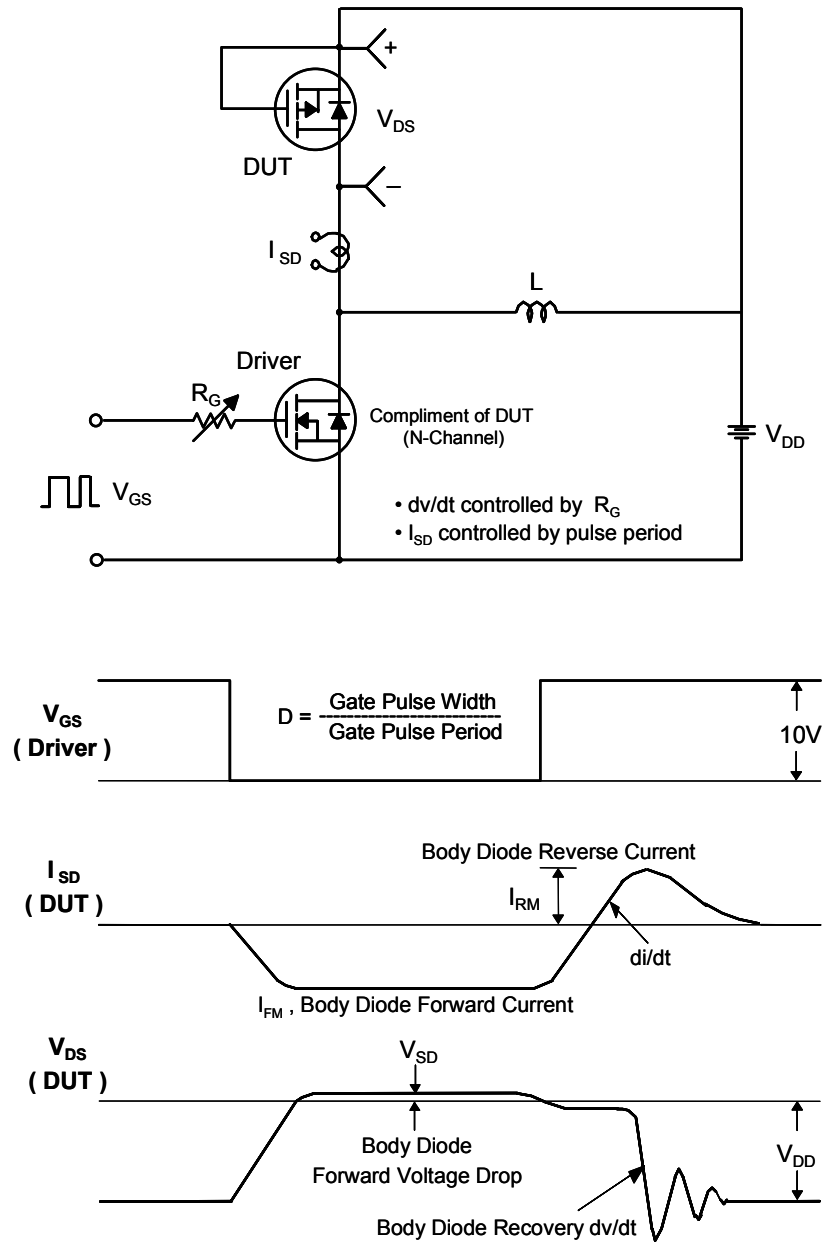
Resistive Switching Test Circuit & Waveforms



Unclamped Inductive Switching Test Circuit & Waveforms

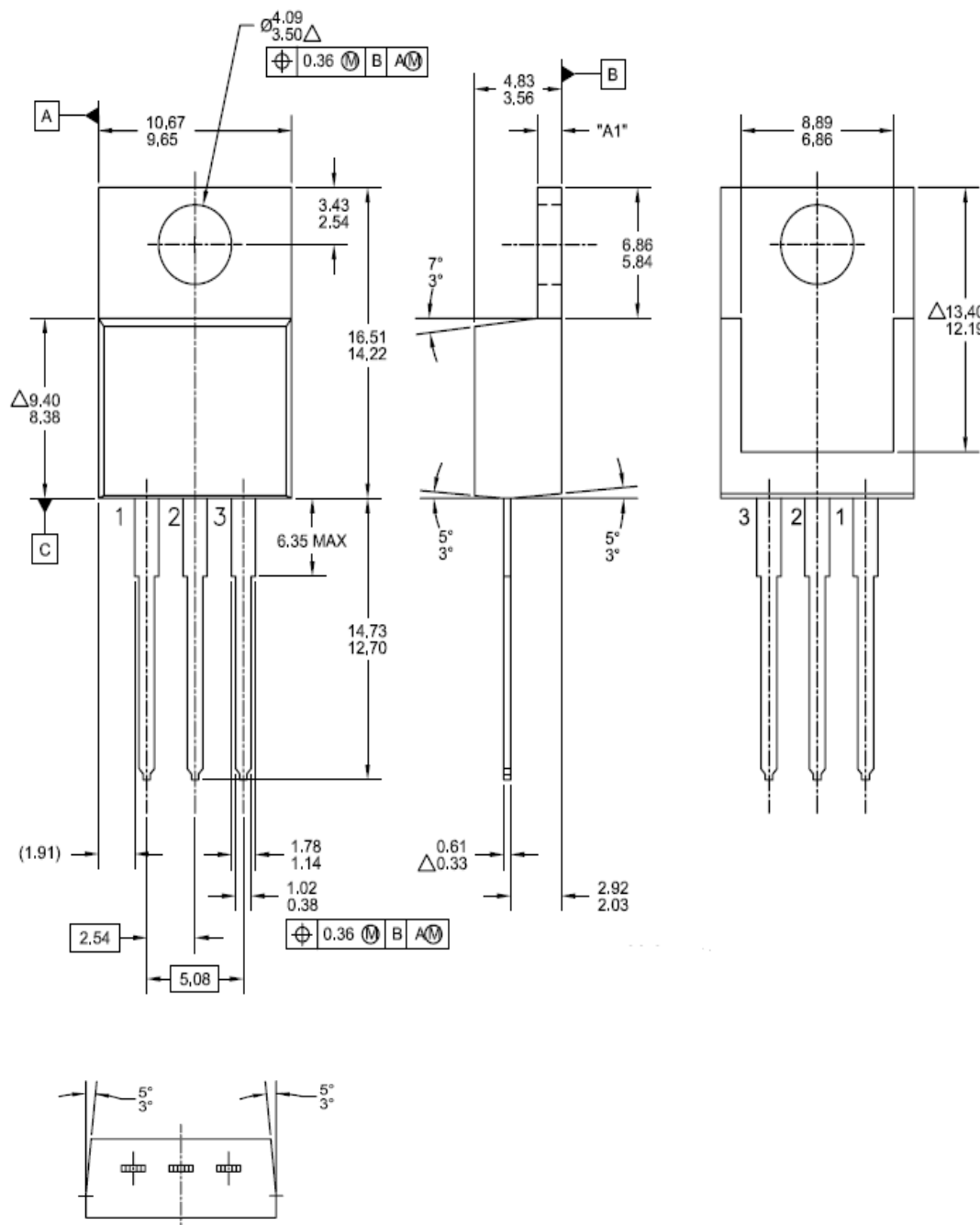


Peak Diode Recovery dv/dt Test Circuit & Waveforms



Package Dimensions

TO - 220



Dimensions in Millimeters

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Bottomless™	FASTr™	PACMAN™	SuperSOT™-6
CoolFET™	FRFET™	POP™	SuperSOT™-8
CROSSVOLT™	GlobalOptoisolator™	PowerTrench [®]	SyncFET™
DenseTrench™	GTO™	QFET™	TinyLogic™
DOME™	HiSeC™	QS™	UHC™
EcoSPARK™	ISOPPLANAR™	QT Optoelectronics™	UltraFET [®]
E ² CMOS™	LittleFET™	Quiet Series™	VCX™
EnSigna™	MicroFET™	SLIENT SWITCHER [®]	
FACT™	MICROWIRE™	SMART START™	
FACT Quiet Series™	OPTOLOGIC™	Stealth™	

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

PRODUCT STATUS DEFINITIONS

Definition of Terms

Datasheet Identification	Product Status	Definition
Advance Information	Formative or In Design	This datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	This datasheet contains preliminary data, and supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
No Identification Needed	Full Production	This datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice in order to improve design.
Obsolete	Not In Production	This datasheet contains specifications on a product that has been discontinued by Fairchild semiconductor. The datasheet is printed for reference information only.

FQP30N06L

N-Channel QFET® MOSFET

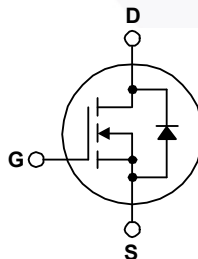
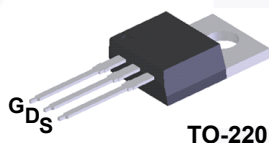
60 V, 32 A, 35 mΩ

Description

This N-Channel enhancement mode power MOSFET is produced using Fairchild Semiconductor's proprietary planar stripe and DMOS technology. This advanced MOSFET technology has been especially tailored to reduce on-state resistance, and to provide superior switching performance and high avalanche energy strength. These devices are suitable for switched mode power supplies, audio amplifier, DC motor control, and variable switching power applications.

Features

- 32 A, 60 V, $R_{DS(on)} = 35 \text{ m}\Omega$ (Max.) @ $V_{GS} = 10 \text{ V}$, $I_D = 16 \text{ A}$
- Low Gate Charge (Typ. 15 nC)
- Low C_{rss} (Typ. 50 pF)
- 100% Avalanche Tested
- 175°C Maximum Junction Temperature Rating



Absolute Maximum Ratings $T_C = 25^\circ\text{C}$ unless otherwise noted.

Symbol	Parameter	FQP30N06L	Unit
V_{DSS}	Drain-Source Voltage	60	V
I_D	Drain Current - Continuous ($T_C = 25^\circ\text{C}$)	32	A
	- Continuous ($T_C = 100^\circ\text{C}$)	22.6	A
I_{DM}	Drain Current - Pulsed (Note 1)	128	A
V_{GSS}	Gate-Source Voltage	± 20	V
E_{AS}	Single Pulsed Avalanche Energy (Note 2)	350	mJ
I_{AR}	Avalanche Current (Note 1)	32	A
E_{AR}	Repetitive Avalanche Energy (Note 1)	7.9	mJ
dv/dt	Peak Diode Recovery dv/dt (Note 3)	7.0	V/ns
P_D	Power Dissipation ($T_C = 25^\circ\text{C}$)	79	W
	- Derate above 25°C	0.53	W/ $^\circ\text{C}$
T_J, T_{STG}	Operating and Storage Temperature Range	-55 to +175	$^\circ\text{C}$
T_L	Maximum Lead Temperature for Soldering, 1/8" from Case for 5 seconds	300	$^\circ\text{C}$

Thermal Characteristics

Symbol	Parameter	FQP30N06L	Unit
$R_{\theta JC}$	Thermal Resistance, Junction-to-Case, Max.	1.90	$^\circ\text{C/W}$
$R_{\theta JA}$	Thermal Resistance, Junction-to-Ambient, Max.	62.5	$^\circ\text{C/W}$

Package Marking and Ordering Information

Part Number	Top Mark	Package	Packing Method	Reel Size	Tape Width	Quantity
FQP30N06L	FQP30N06L	TO-220	Tube	N/A	N/A	50 units

Electrical Characteristics

$T_C = 25^\circ\text{C}$ unless otherwise noted.

Symbol	Parameter	Test Conditions	Min	Typ	Max	Unit
--------	-----------	-----------------	-----	-----	-----	------

Off Characteristics

BV_{DSS}	Drain-Source Breakdown Voltage	$V_{GS} = 0\text{ V}, I_D = 250\text{ }\mu\text{A}$	60	--	--	V
$\Delta BV_{DSS} / \Delta T_J$	Breakdown Voltage Temperature Coefficient	$I_D = 250\text{ }\mu\text{A}$, Referenced to 25°C	--	0.06	--	V/ $^\circ\text{C}$
I_{DSS}	Zero Gate Voltage Drain Current	$V_{DS} = 60\text{ V}, V_{GS} = 0\text{ V}$	--	--	1	μA
		$V_{DS} = 48\text{ V}, T_C = 150^\circ\text{C}$	--	--	10	μA
I_{GSSF}	Gate-Body Leakage Current, Forward	$V_{GS} = 20\text{ V}, V_{DS} = 0\text{ V}$	--	--	100	nA
I_{GSSR}	Gate-Body Leakage Current, Reverse	$V_{GS} = -20\text{ V}, V_{DS} = 0\text{ V}$	--	--	-100	nA

On Characteristics

$V_{GS(th)}$	Gate Threshold Voltage	$V_{DS} = V_{GS}, I_D = 250\text{ }\mu\text{A}$	1.0	--	2.5	V
$R_{DS(on)}$	Static Drain-Source On-Resistance	$V_{GS} = 10\text{ V}, I_D = 16\text{ A}$	--	0.027	0.035	Ω
		$V_{GS} = 5\text{ V}, I_D = 16\text{ A}$	--	0.035	0.045	Ω
g_{FS}	Forward Transconductance	$V_{DS} = 25\text{ V}, I_D = 16\text{ A}$	--	24	--	S

Dynamic Characteristics

C_{iss}	Input Capacitance	$V_{DS} = 25\text{ V}, V_{GS} = 0\text{ V},$ $f = 1.0\text{ MHz}$	--	800	1040	pF
C_{oss}	Output Capacitance		--	270	350	pF
C_{rss}	Reverse Transfer Capacitance		--	50	65	pF

Switching Characteristics

$t_{d(on)}$	Turn-On Delay Time	$V_{DD} = 30\text{ V}, I_D = 16\text{ A},$ $R_G = 25\text{ }\Omega$	--	15	40	ns
t_r	Turn-On Rise Time		--	210	430	ns
$t_{d(off)}$	Turn-Off Delay Time		--	60	130	ns
t_f	Turn-Off Fall Time		--	110	230	ns
Q_g	Total Gate Charge	$V_{DS} = 48\text{ V}, I_D = 32\text{ A},$ $V_{GS} = 5\text{ V}$	--	15	20	nC
Q_{gs}	Gate-Source Charge		--	3.5	--	nC
Q_{gd}	Gate-Drain Charge		--	8.5	--	nC

Drain-Source Diode Characteristics and Maximum Ratings

I _S	Maximum Continuous Drain-Source Diode Forward Current		--	--	32	A
I _{SM}	Maximum Pulsed Drain-Source Diode Forward Current		--	--	128	A
V _{SD}	Drain-Source Diode Forward Voltage	V _{GS} = 0 V, I _S = 32 A	--	--	1.5	V
t _{rr}	Reverse Recovery Time	V _{GS} = 0 V, I _S = 32 A, dI _F / dt = 100 A/μs	--	60	--	ns
Q _{rr}	Reverse Recovery Charge		--	90	--	nC

Notes:

1. Repetitive Rating : Pulse width limited by maximum junction temperature.
2. $L = 400\text{ }\mu\text{H}$, $I_{AS} = 32\text{ A}$, $V_{DD} = 25\text{ V}$, $R_G = 25\text{ }\Omega$, starting $T_J = 25^\circ\text{C}$.
3. $I_{SD} \leq 32\text{ A}$, $dI/dt \leq 300\text{ A}/\mu\text{s}$, $V_{DD} \leq BV_{DSS}$, starting $T_J = 25^\circ\text{C}$.
4. Essentially independent of operating temperature.

Typical Characteristics

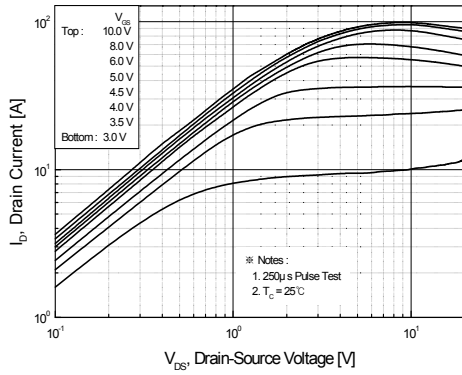


Figure 1. On-Region Characteristics

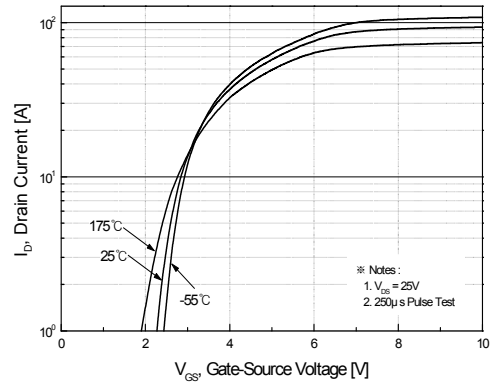


Figure 2. Transfer Characteristics

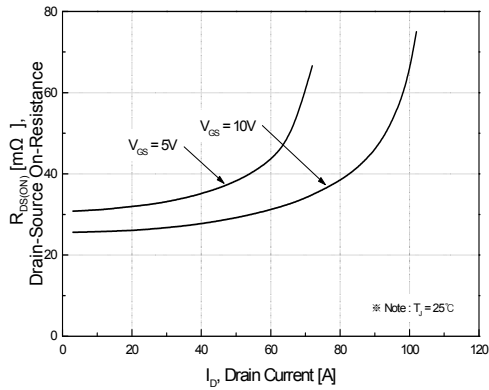


Figure 3. On-Resistance Variation vs. Drain Current and Gate Voltage

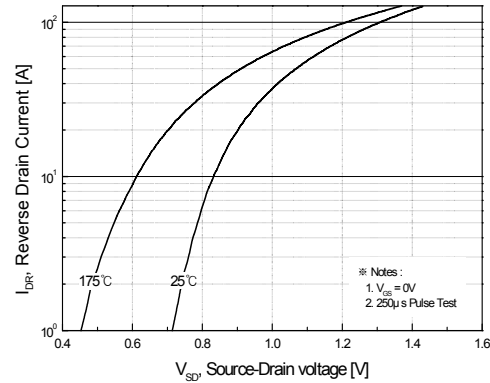


Figure 4. Body Diode Forward Voltage Variation vs. Source Current and Temperature

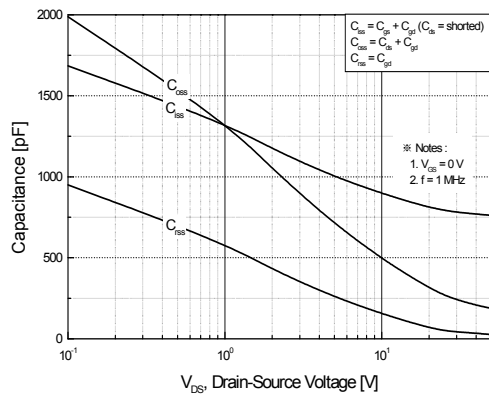


Figure 5. Capacitance Characteristics

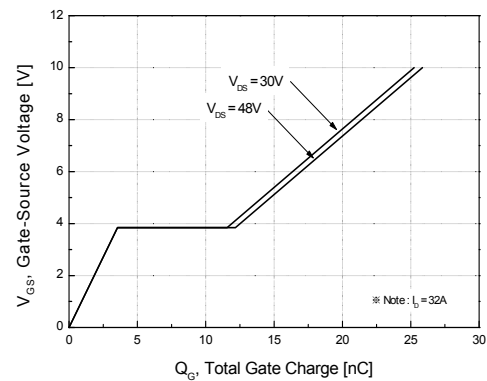


Figure 6. Gate Charge Characteristics

Typical Characteristics (continued)

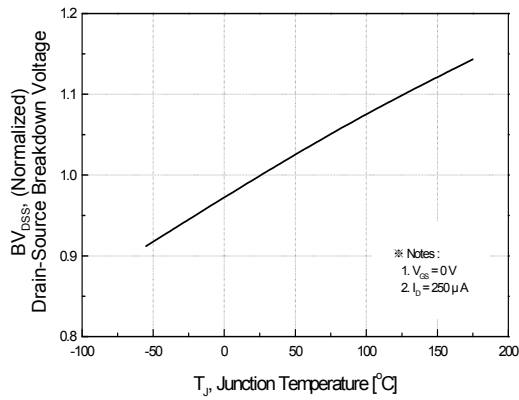


Figure 7. Breakdown Voltage Variation vs. Temperature

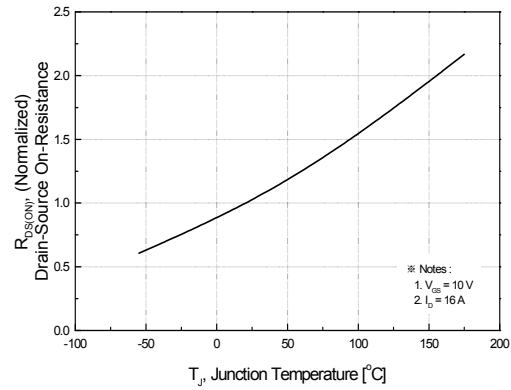


Figure 8. On-Resistance Variation vs. Temperature

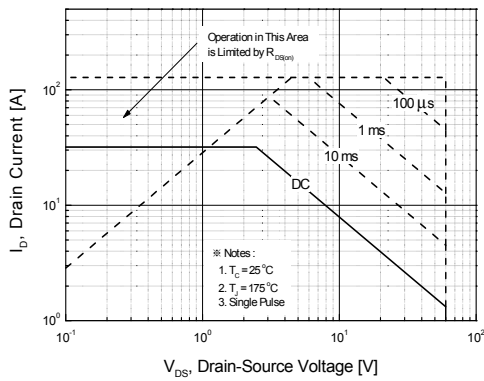


Figure 9. Maximum Safe Operating Area

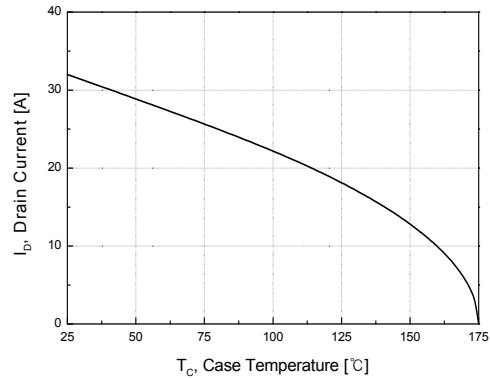


Figure 10. Maximum Drain Current vs. Case Temperature

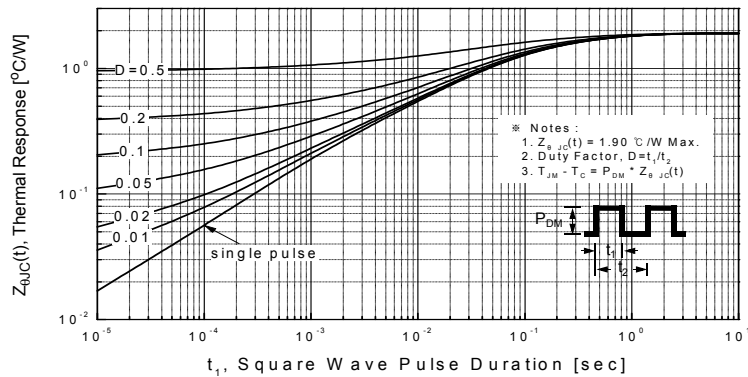


Figure 11. Transient Thermal Response Curve

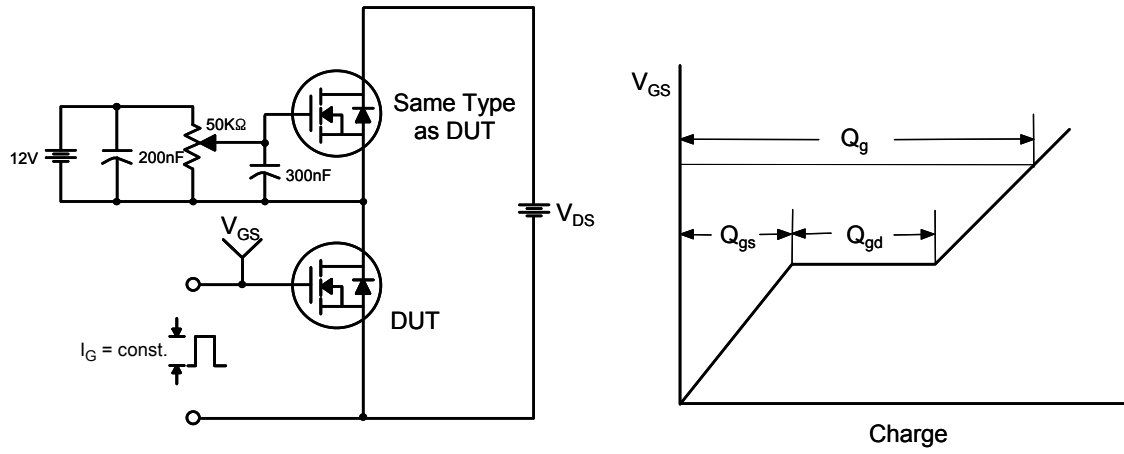


Figure 12. Gate Charge Test Circuit & Waveform

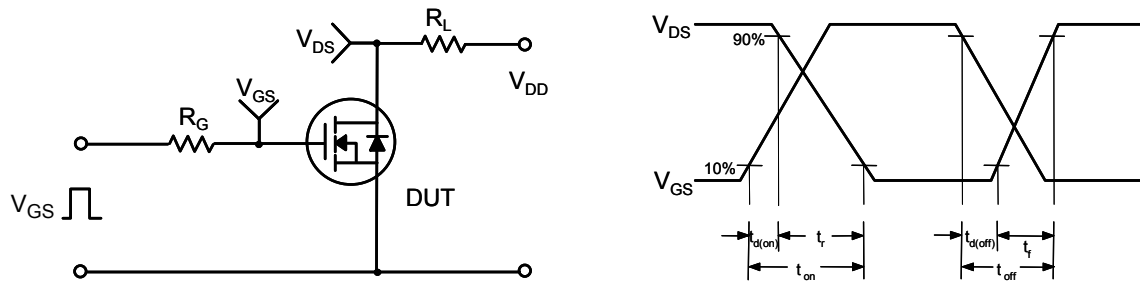


Figure 13. Resistive Switching Test Circuit & Waveforms

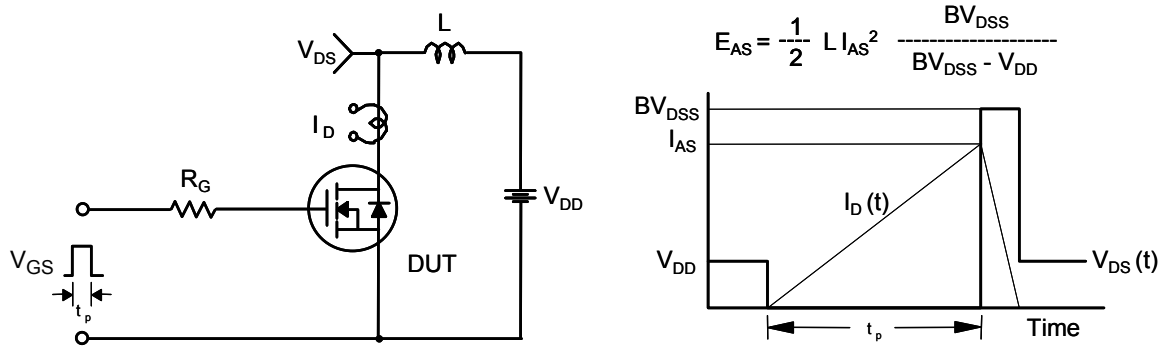


Figure 14. Unclamped Inductive Switching Test Circuit & Waveforms

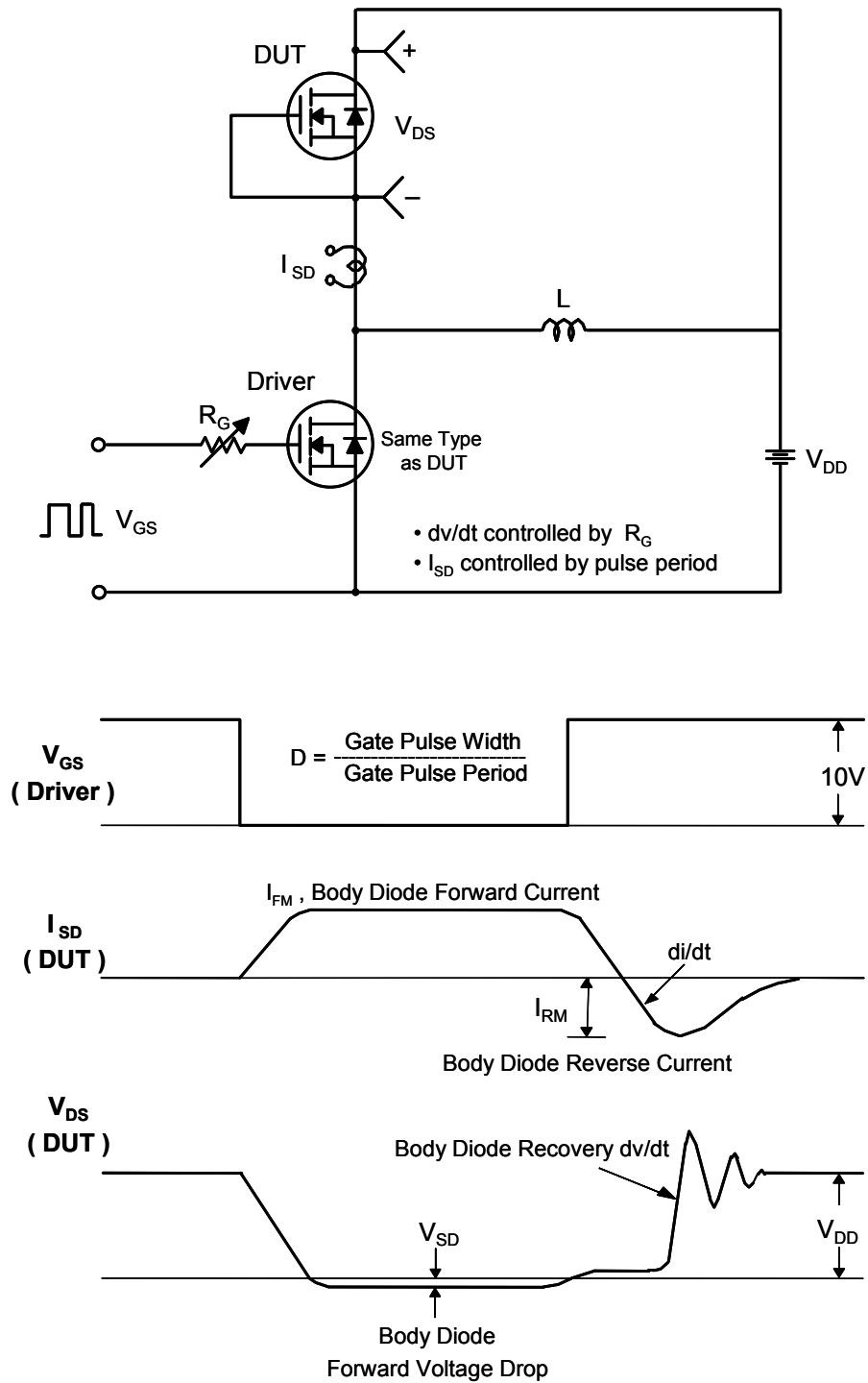


Figure 15. Peak Diode Recovery dv/dt Test Circuit & Waveforms

Mechanical Dimensions

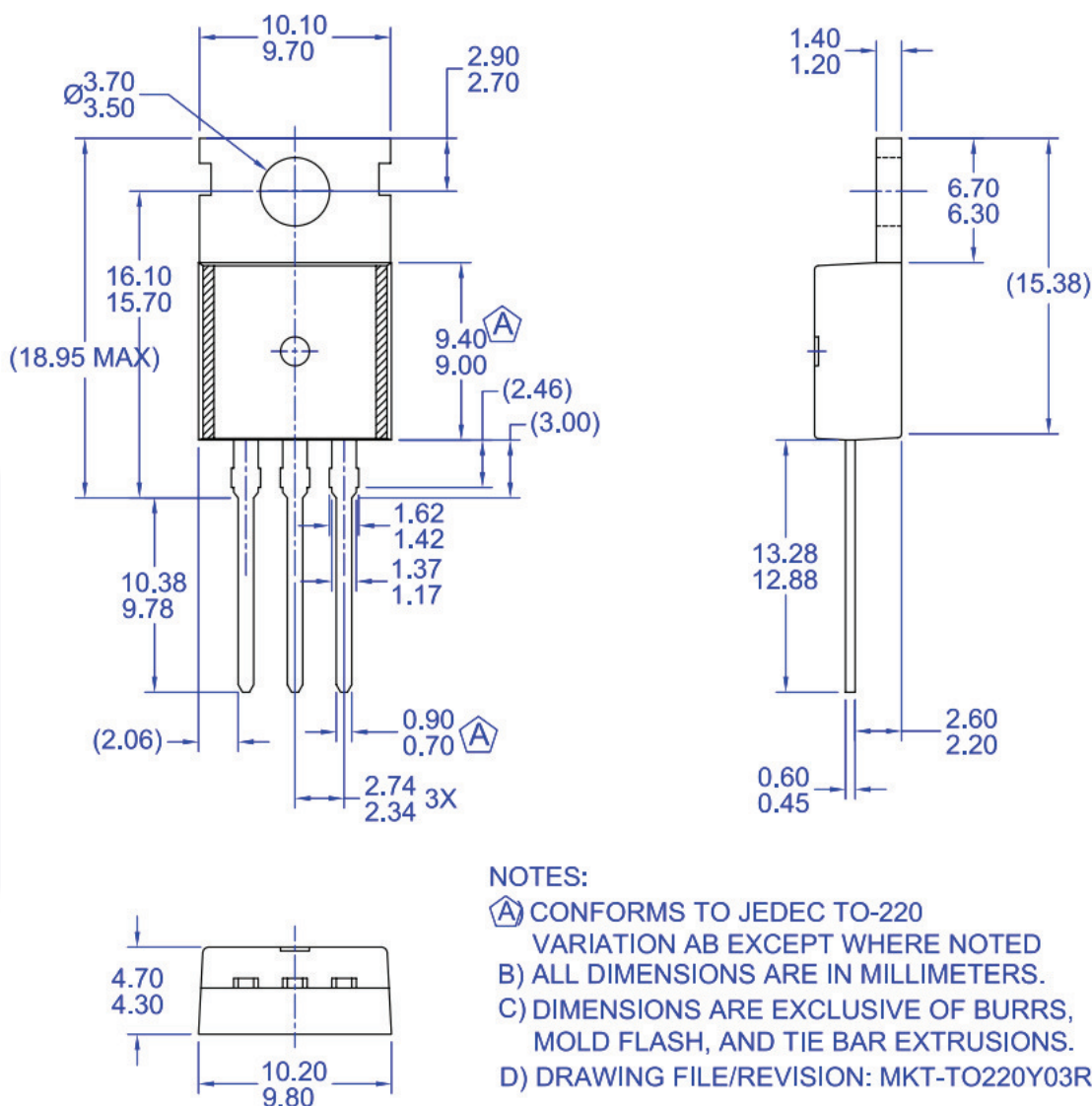


Figure 16. TO220, Molded, 3-Lead, Jedec Variation AB

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Datasheet Identification	Product Status	Definition
Advance Information	Formative / In Design	Datasheet contains the design specifications for product development. Specifications may change in any manner without notice.
Preliminary	First Production	Datasheet contains preliminary data; supplementary data will be published at a later date. Fairchild Semiconductor reserves the right to make changes at any time without notice to improve design.
No Identification Needed	Full Production	Datasheet contains final specifications. Fairchild Semiconductor reserves the right to make changes at any time without notice to improve the design.
Obsolete	Not In Production	Datasheet contains specifications on a product that is discontinued by Fairchild Semiconductor. The datasheet is for reference information only.

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2N3904

SMALL SIGNAL NPN TRANSISTOR

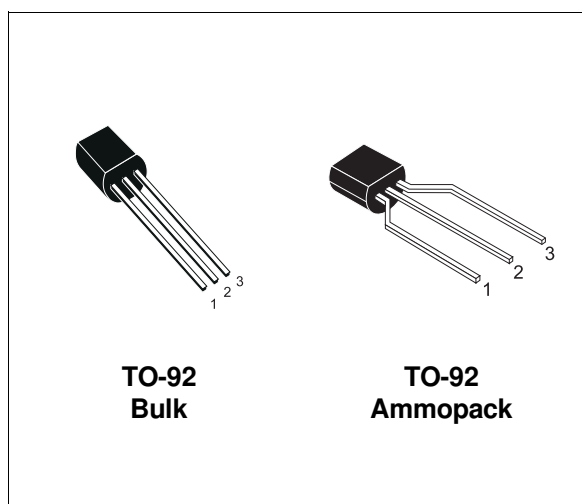
PRELIMINARY DATA

Ordering Code	Marking	Package / Shipment
2N3904	2N3904	TO-92 / Bulk
2N3904-AP	2N3904	TO-92 / Ammopack

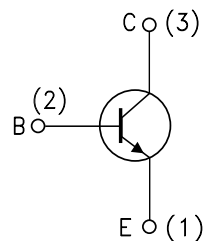
- SILICON EPITAXIAL PLANAR NPN TRANSISTOR
- TO-92 PACKAGE SUITABLE FOR THROUGH-HOLE PCB ASSEMBLY
- THE PNP COMPLEMENTARY TYPE IS 2N3906

APPLICATIONS

- WELL SUITABLE FOR TV AND HOME APPLIANCE EQUIPMENT
- SMALL LOAD SWITCH TRANSISTOR WITH HIGH GAIN AND LOW SATURATION VOLTAGE



INTERNAL SCHEMATIC DIAGRAM



ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Value	Unit
V_{CBO}	Collector-Base Voltage ($I_E = 0$)	60	V
V_{CEO}	Collector-Emitter Voltage ($I_B = 0$)	40	V
V_{EBO}	Emitter-Base Voltage ($I_C = 0$)	6	V
I_C	Collector Current	200	mA
P_{tot}	Total Dissipation at $T_C = 25\text{ }^{\circ}\text{C}$	625	mW
T_{stg}	Storage Temperature	-65 to 150	$^{\circ}\text{C}$
T_j	Max. Operating Junction Temperature	150	$^{\circ}\text{C}$

THERMAL DATA

$R_{thj-amb}$ •	Thermal Resistance Junction-Ambient	Max	200	$^{\circ}\text{C/W}$
$R_{thj-case}$ •	Thermal Resistance Junction-Case	Max	83.3	$^{\circ}\text{C/W}$

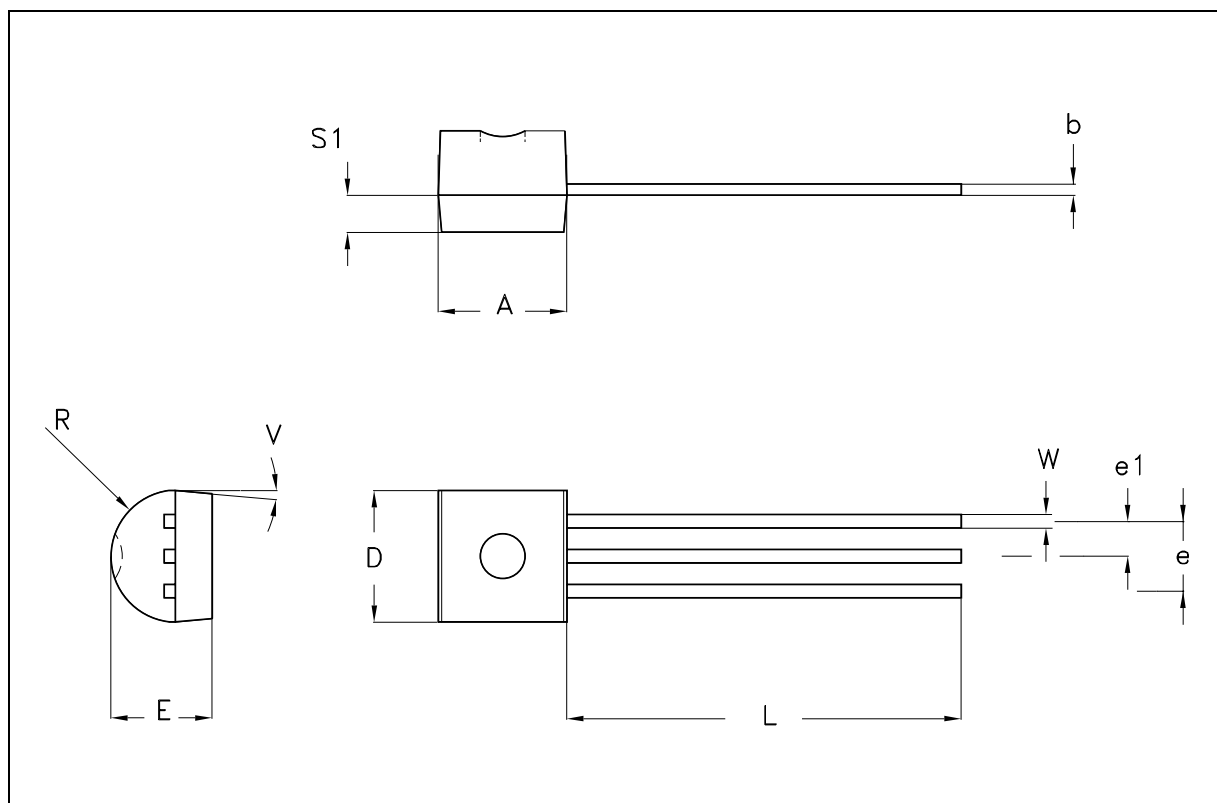
ELECTRICAL CHARACTERISTICS ($T_{case} = 25^{\circ}\text{C}$ unless otherwise specified)

Symbol	Parameter	Test Conditions	Min.	Typ.	Max.	Unit
I_{CEX}	Collector Cut-off Current ($V_{BE} = -3\text{ V}$)	$V_{CE} = 30\text{ V}$			50	nA
I_{BEX}	Base Cut-off Current ($V_{BE} = -3\text{ V}$)	$V_{CE} = 30\text{ V}$			50	nA
$V_{(BR)CEO}^{*}$	Collector-Emitter Breakdown Voltage ($I_B = 0$)	$I_C = 1\text{ mA}$	40			V
$V_{(BR)CBO}$	Collector-Base Breakdown Voltage ($I_E = 0$)	$I_C = 10\text{ }\mu\text{A}$	60			V
$V_{(BR)EBO}$	Emitter-Base Breakdown Voltage ($I_C = 0$)	$I_E = 10\text{ }\mu\text{A}$	6			V
$V_{CE(sat)}^{*}$	Collector-Emitter Saturation Voltage	$I_C = 10\text{ mA}$ $I_B = 1\text{ mA}$ $I_C = 50\text{ mA}$ $I_B = 5\text{ mA}$			0.2 0.2	V V
$V_{BE(sat)}^{*}$	Base-Emitter Saturation Voltage	$I_C = 10\text{ mA}$ $I_B = 1\text{ mA}$ $I_C = 50\text{ mA}$ $I_B = 5\text{ mA}$	0.65		0.85 0.95	V V
h_{FE}^{*}	DC Current Gain	$I_C = 0.1\text{ mA}$ $V_{CE} = 1\text{ V}$ $I_C = 1\text{ mA}$ $V_{CE} = 1\text{ V}$ $I_C = 10\text{ mA}$ $V_{CE} = 1\text{ V}$ $I_C = 50\text{ mA}$ $V_{CE} = 1\text{ V}$ $I_C = 100\text{ mA}$ $V_{CE} = 1\text{ V}$	60 80 100 60 30		300	
f_T	Transition Frequency	$I_C = 10\text{ mA}$ $V_{CE} = 20\text{ V}$ $f = 100\text{ MHz}$	250	270		MHz
C_{CBO}	Collector-Base Capacitance	$I_E = 0$ $V_{CB} = 10\text{ V}$ $f = 1\text{ MHz}$		4		pF
C_{EBO}	Emitter-Base Capacitance	$I_C = 0$ $V_{EB} = 0.5\text{ V}$ $f = 1\text{ MHz}$		18		pF
NF	Noise Figure	$V_{CE} = 5\text{ V}$ $I_C = 0.1\text{ mA}$ $f = 10\text{ Hz}$ to 15.7 KHz $R_G = 1\text{ K}\Omega$		5		dB
t_d	Delay Time	$I_C = 10\text{ mA}$ $I_B = 1\text{ mA}$			35	ns
t_r	Rise Time	$V_{CC} = 30\text{ V}$			35	ns
t_s	Storage Time	$I_C = 10\text{ mA}$ $I_{B1} = -I_{B2} = 1\text{ mA}$			200	ns
t_f	Fall Time	$V_{CC} = 30\text{ V}$			50	ns

* Pulsed: Pulse duration = 300 μs , duty cycle $\leq 2\%$

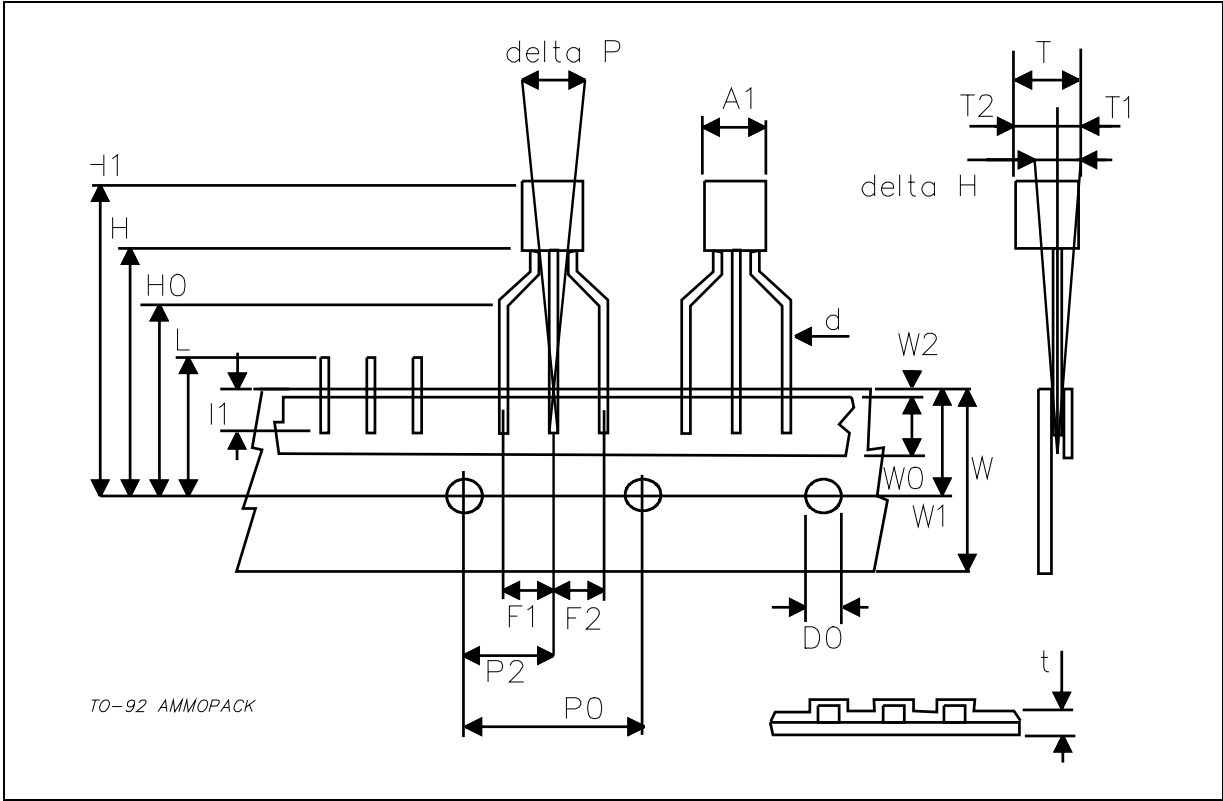
TO-92 MECHANICAL DATA

DIM.	mm			inch		
	MIN.	TYP.	MAX.	MIN.	TYP.	MAX.
A	4.32		4.95	0.170		0.195
b	0.36		0.51	0.014		0.020
D	4.45		4.95	0.175		0.194
E	3.30		3.94	0.130		0.155
e	2.41		2.67	0.095		0.105
e1	1.14		1.40	0.045		0.055
L	12.70		15.49	0.500		0.609
R	2.16		2.41	0.085		0.094
S1	1.14		1.52	0.045		0.059
W	0.41		0.56	0.016		0.022
V	4 degree		6 degree	4 degree		6 degree



TO-92 AMMOPACK SHIPMENT (Suffix"-AP") MECHANICAL DATA

DIM.	mm			inch		
	MIN.	TYP.	MAX.	MIN.	TYP.	MAX.
A1			4.80			0.189
T			3.80			0.150
T1			1.60			0.063
T2			2.30			0.091
d			0.48			0.019
P0	12.50	12.70	12.90	0.492	0.500	0.508
P2	5.65	6.35	7.05	0.222	0.250	0.278
F1,F2	2.44	2.54	2.94	0.096	0.100	0.116
delta H	-2.00		2.00	-0.079		0.079
W	17.50	18.00	19.00	0.689	0.709	0.748
W0	5.70	6.00	6.30	0.224	0.236	0.248
W1	8.50	9.00	9.25	0.335	0.354	0.364
W2			0.50			0.020
H	18.50		20.50	0.728		0.807
H0	15.50	16.00	16.50	0.610	0.630	0.650
H1			25.00			0.984
D0	3.80	4.00	4.20	0.150	0.157	0.165
t			0.90			0.035
L			11.00			0.433
I1	3.00			0.118		
delta P	-1.00		1.00	-0.039		0.039



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APPENDIX D: Arduino Code

```
const int MDSPin = A2; // Joystick x-input
const int steerPin = A1; // Joystick y-input
const int motor1Pin = 3; // Control1
const int motor2Pin = 5; // Control2
const int steerVolt = 6; // NINO Steering
const int limitPin1 = 9; // Front Limit
const int limitPin2 = 13; // Back Limit
```

```
int MDSVal = 0;
int steerVal = 0;
int MDSnew = 0;
int MDSold = 0;
int limitVal1 = 0;
int limitVal2 = 0;
int a = 1; //increase for faster response
int b = 8; //increase for smoother response
```

```
int period = 20; //ms
int pw = 900; // micro seconds
int newSteerVal = 0;
```

```
void setup() {
  Serial.begin(9600);
  // set the joystick as an input:
  pinMode(MDSPin, INPUT);
  pinMode(steerPin, INPUT);
  pinMode(limitPin1, INPUT);
  pinMode(limitPin2, INPUT);
  // set all the other pins as outputs:
  pinMode(motor1Pin, OUTPUT);
  pinMode(motor2Pin, OUTPUT);
  pinMode(steerVolt, OUTPUT);
}
```

```
void loop() {
  MDSVal = analogRead(MDSPin);
  newSteerVal = analogRead(steerPin);
  if (newSteerVal != steerVal) {
    steerVal = newSteerVal;
  }
  // Serial.println(steerVal);
  //Lazy Filter for joystick MDS speed
  MDSnew = ((a*MDSVal) + (b*MDSold))/(a+b);
  MDSold = MDSnew;
```

```
//Reading limit switches' input
limitVal1 = digitalRead(limitPin1);
limitVal2 = digitalRead(limitPin2);

//Map MDS and Steer value to arduino outputs to motor and steering
int MDS = map(MDSVal, 0, 1023, 100, -100);
if (MDS > 5) {
    int MDS2 = MDS + 40;
    MDS = MDS2;
}
Serial.println(MDS);
```

```
pw = map(newSteerVal, 0, 1023, 653, 757); // center 704
if (pw > 710) {
    int pw2 = pw + 15;
    pw = pw2;
}
if (pw < 708 and pw > 698) {
    pw = 702;
}
```

```
for (int i=0; i<3; i++) {
    // Set the output pin high for the length of the necessary pulse
    digitalWrite(steerVolt, HIGH);
    delayMicroseconds(pw);

    // Set the output pin low for the rest of the period
    digitalWrite(steerVolt, LOW);
    delay(period - pw/1000);
}
```

```
// Motor turn in one direction:
if (MDS > 15) {
```

```
    // When MDS hits the front end of rack, stop sending voltage
    if (limitVal1 == HIGH) {
        analogWrite(motor1Pin, 0); // send low to control1
        analogWrite(motor2Pin, 0); // send low to control2
    }
    else {
        analogWrite(motor1Pin, 0); // send low to control1
        analogWrite(motor2Pin, MDS); // send high to control2
    }
}
```

```

    //Serial.println(pw);
  }
}

// Motor turn in the other direction:
else if (MDS < -15) {

  // When MDS hits the back end of rack, stop sending voltage
  if (limitVal2 == HIGH) {
    analogWrite(motor1Pin, 0); // send low to control1
    analogWrite(motor2Pin, 0); // send low to control2
  }
  else {
    analogWrite(motor1Pin, abs(MDS)); // send high to control1
    analogWrite(motor2Pin, 0); // send low to control2
    //Serial.println(abs(pw));

  }
}

else {
  analogWrite(motor1Pin, 0); // send low to control1
  analogWrite(motor2Pin, 0); // send low to control2
}
delay(100);
}

```