

CHAPTER 4 – RESULTS AND DISCUSSIONS

4.1 Mechanical Design

The AMR structure is supported through the hollow steel frame welded with stainless steel base as well. The design prioritizes both operational durability in industrial environment and ease of maintenance.

4.1.1 Computer Aided Design and Justification

The mechanical design of the AMR was developed using SolidWorks to ensure precise spatial optimization.

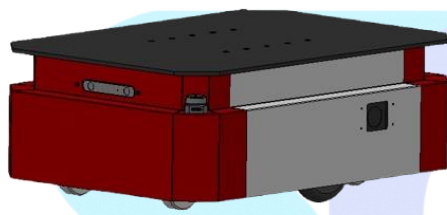


Figure 4.1 AMR Design View 1

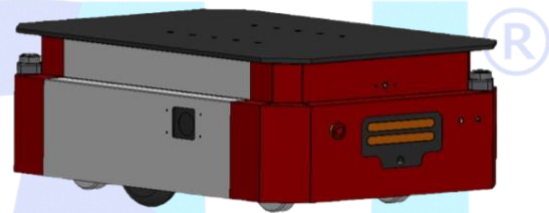


Figure 4.2 AMR Design View 2

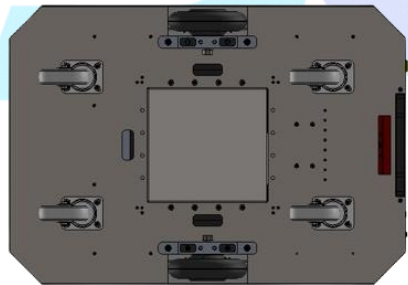


Figure 4.3 AMR Bottom View

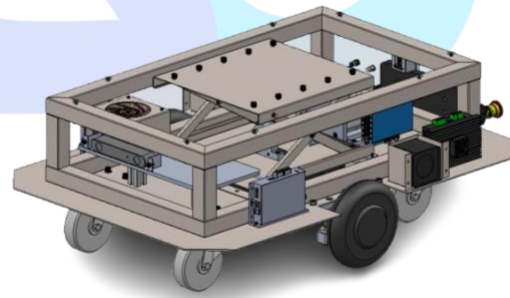


Figure 4.4 AMR Internal View

The AMR's dimension (L x W x H) is (1000 x 700 x 350) mm. The wheel configuration is 2 drive wheels on left and right side and 4 caster wheels, 2 caster each at the front side and at the back side. It consists of the main structure, wheel suspension mechanism, scissor lift mechanism and other small supporting parts. The LiDARs are placed diagonally at the left front and right back part of the body. There is a charging copper on the back side of the robot for charging when docked. ZED 2 camera is mounted up front as 3D support for visual SLAM.

4.1.1.1 Main Structure

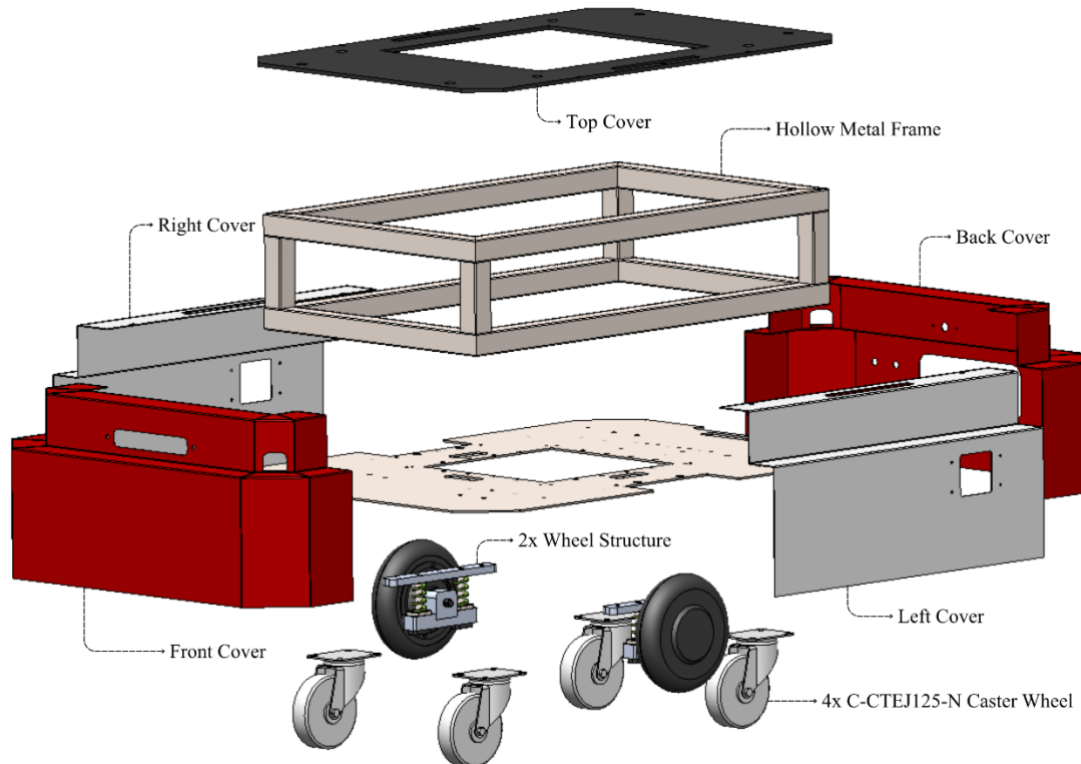


Figure 4.5 AMR Main Structure Exploded View

The main structure of the AMR consists of a frame made out of hollow steel and a base plate. The structure consists of 38mm x 38mm 2mm thick hollow steel beams. The dimension (L x W x H) for this frame is (840 x 500 x 176) mm. They are welded together to create a strong bond and hold the weight required. The base plate for this AMR has several holes to support the attachment of the components including the caster wheels, drive wheel mount, aluminum profiles, charger base, etc. It is made out of stainless steel and will be welded with the hollow steel frame. The base plate's dimension is (1000 x 700 x 3) mm.

The AMR also has its own cover to hide the structure and cover the components for aesthetic and functional purposes. The covers are constructed by using stainless steel sheet metal bent. The front side of the AMR includes the cover and also act as the mounting place of the ZED 2 Depth Camera and the RPLiDAR S3. It also has a small rectangular hole area specifically for the LiDAR's cable to go inside of the body. The back side of the AMR includes the cover and also act as the mounting place of the Arducam OV9782 and the RPLiDAR S3. It also has a small rectangular hole area

specifically for the LiDAR's cable to go inside of the body. There is also a through area for the charger copper to come in contact with the charging dock area. Buttons such as emergency stop, power button and stop button are also mounted on the back cover. The left and right-side cover features a mounting hole and the through area for the speaker.

4.1.1.3 Wheel Structure

The drive wheel used is ZLTECH's ZLLG80ASM250L V3.0. To add suspension to the AMR, some structures are needed as support. The suspension system used for this robot is using spring suspension only on the drive wheel. This is to keep all of the wheels compliant as the caster wheels are not suspended. The spring used here is the SWH25-50 by Misumi. It has an outer diameter of 25mm and length of 50mm with maximum load of 1833N. It is also supported with FBJ LMH16UU Linear Bushings for the suspension rod's linear movement.

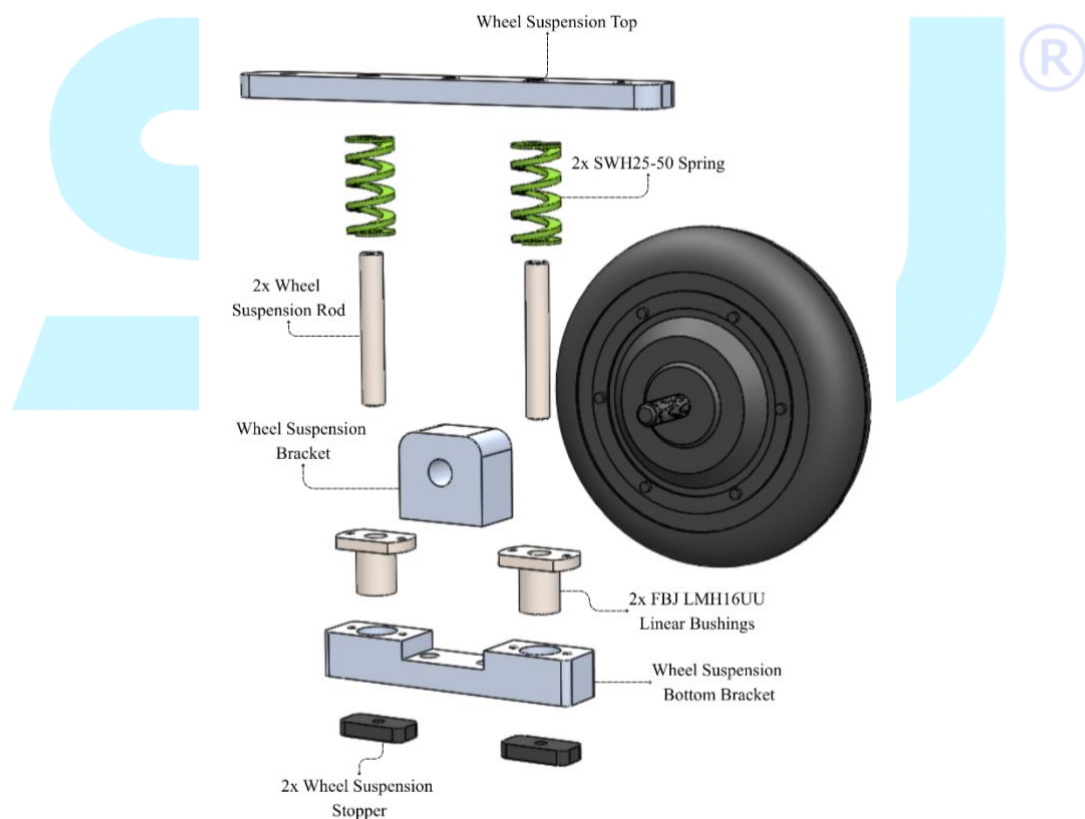


Figure 4.6 Wheel Suspension Mechanism Exploded View

The rod for the wheel suspension is made out of 201 Stainless Steel and has a dimension of outer diameter (OD) of 12mm and length of 80mm. There is threaded M6x1.0 hole to attach the rod to the mounting and the stopper. The top part of the wheel suspension is to mount the rod and the brackets for the drive wheel. It is made out of Aluminum

1060 Alloy and has a dimension of (250 x 30 x 12) mm. The wheel suspension wheel bracket consists of two parts; it is separated due to its geometry and complexity of manufacture. It is made out of Aluminum 1060 Alloy. Wheel Bracket Base has a dimension of (150 x 30 x 24) mm while the Wheel Bracket has a dimension of (50 x 46 x 30) mm. These two parts are to connect the drive wheel and the suspension rods. The wheel suspension stopper is made to stop the suspension spring from over extension. It is made out of Bakelite material and has a dimension of (40 x 20 x 8) mm.

4.1.1.4 Scissor Lift Mechanism

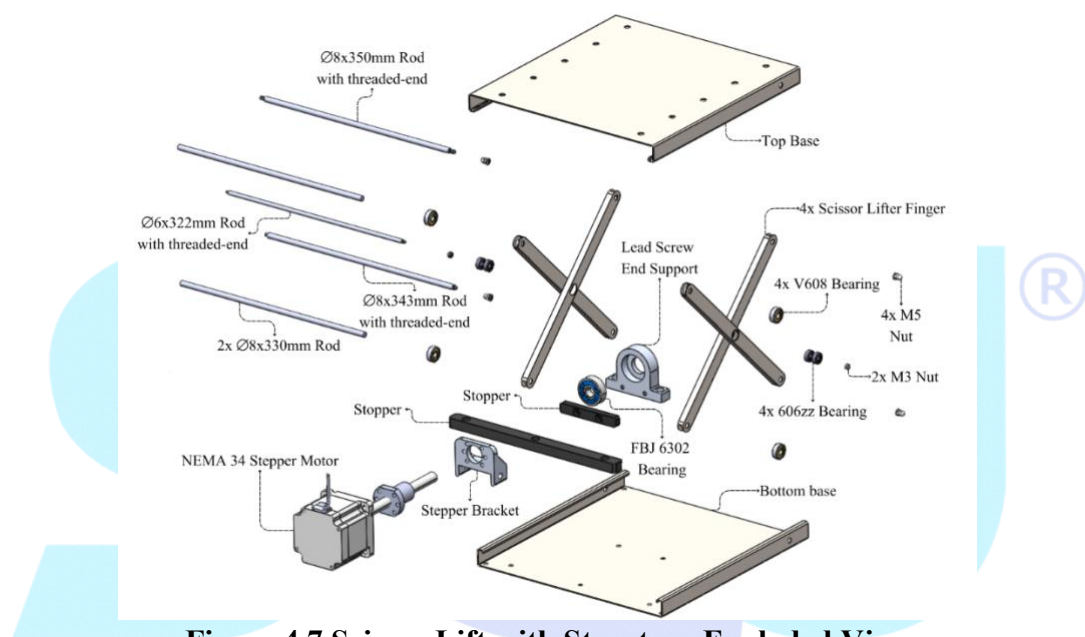


Figure 4.7 Scissor Lift with Structure Exploded View

The scissor lift mechanism uses a NEMA 34 Stepper Motor with lead screw as the actuator. This actuator is chosen based on the justification in 3.5.1.9. The lead screw coupling is then connected to the free rod that connects the scissor lift fingers. For the rolling mechanism on the rods and bases, V608 Bearing is selected to provide smooth rolling motion with enough support. The bottom base for the scissor lifter is made out of 201 Stainless Steel 1.5mm thick bent according to the design to support the V608 bearings and has a dimension of (350 x 333 x 26.5) mm. It is also the base to mount the lead screw end support and stoppers. The top part of the scissor lifter is made out of 201 Stainless Steel 1.5mm thick be and has a dimension of (350 x 333 x 26.5) mm. It acts as the connector between the scissor lift and the top lifter part. It is connected with the V608 Bearings. The fingers for the scissor lifter are made out of 10 x 20 x 1mm hollow steel with a dimension of (320 x 20 x 10) mm This part is mounted with the rods

and linked with the bearing for support. The fingers are connected with stainless steel rods with sizes such as M8x350mm, M8x343mm, M8x330mm, and M6x320mm. The difference in sizes is due to the placement of the fingers. The bracket and end support for the NEMA 34 are made out of Aluminum 1060 Alloy, while the stoppers are made out of Bakelite.

4.1.1.4.2 Scaled-down Scissor Lifter

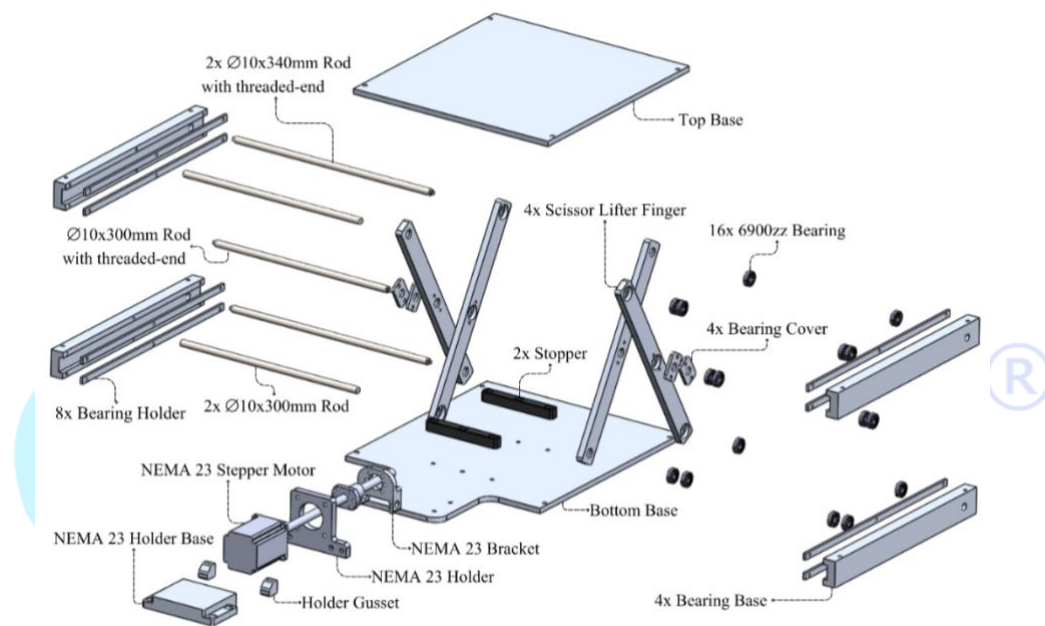


Figure 4.8 Scaled-down Scissor Lifter Prototype Structure Exploded View

The scaled-down scissor lifter prototype uses a NEMA 23 Stepper Motor with lead screw as the actuator. The whole mechanism is similar to the designed scissor lift for the AMR, only the material and additional parts are different. All of the fabricated parts are from 1060 Alloy Aluminum and the shafts are of 201 Stainless Steel. The top and bottom base are separate parts with the bearing base, unlike the original bent sheet metal design. The top base is made out of 8mm thick aluminum with the same width and length dimension as the original design. The bottom base is also made out of 8mm thick aluminum with additional stepper motor brackets placement. The bearing used for this design is the 6900zz bearing. The fingers are made out of 10mm thick aluminum with the same dimension as the original design, this ensure the strength of the fingers but also keeping it lightweight.

4.2 Procurement Issue Context

Due to shipping, procurement, and time issues, it is decided for this research to utilize the available hardware. The AMR mechanical design will only be validated through FEA and will not be fabricated.



Figure 4.9 Previous AMR Hardware

Only the main moving part will be modified for this research, the 3-leveled body will not be used. The previous hardware is primarily made out of aluminum and the main frame is constructed with 40x40mm T-Slot aluminum profile. The dimension (L x W x H) for this hardware is (600x500x370) mm. To be able to imitate the 2 LiDAR scanning concept, the top mounting plate of the previous hardware is modified.

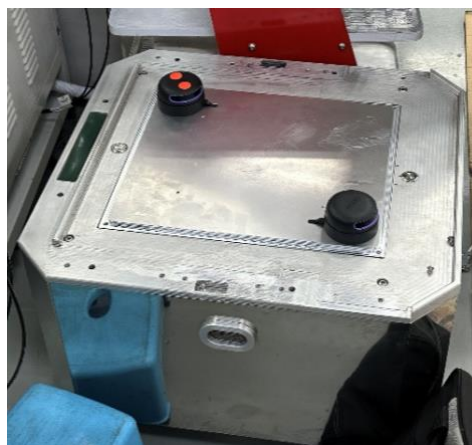


Figure 4.10 Modified LiDAR Mounting Plate

With this plate, the LiDARs are mounted 148.14mm to the front and 123.14mm to the side from the center. The LiDARs used for the testing are also available from the previous hardware, they are RPLiDAR A2M7-R5 and RPLiDAR A2M12.

The mini pc used for this testing is an American Megatrends based mini pc with Intel Core i5-4200U, 8GB DDR3 1600MHz, 256GB SSD, with Ubuntu 20.04 installed. The drive wheels used here are the ZLTech ZLLG45ASM200 V1.0. The battery used is a 24V 20Ah forklift battery. ROS Noetic is used for this testing, it is already available in the mini pc, and upgrading it to ROS 2 would take more time than what is available. The navigation stack used here is the Turtlebot3 Burger with GMCL SLAM. To answer the 3rd research question, the effects of each navigational component will be tested with these specifications. As for the scissor lifter actuator, NEMA 23 Stepper Motor will be used.

4.3 Mechanical Structure Test

This test is conducted to validate that the proposed design meets the structural safety requirement established in H1. FEA is performed in SolidWorks on two assemblies and one part, the scissor lift, the AMR chassis, and the top lifter. This simulation is done under the worst-case load condition. Each simulation is evaluated for their maximum von Mises stress, Factor of Safety (FoS), and resultant displacement. The minimum FoS of 1.5-2.0 is required to confirm structural validity for industrial material handling operations.

4.3.1. Scissor Lift

For the scissor lift structure, only the fingers and the linked parts are analyzed for ease of analysis.

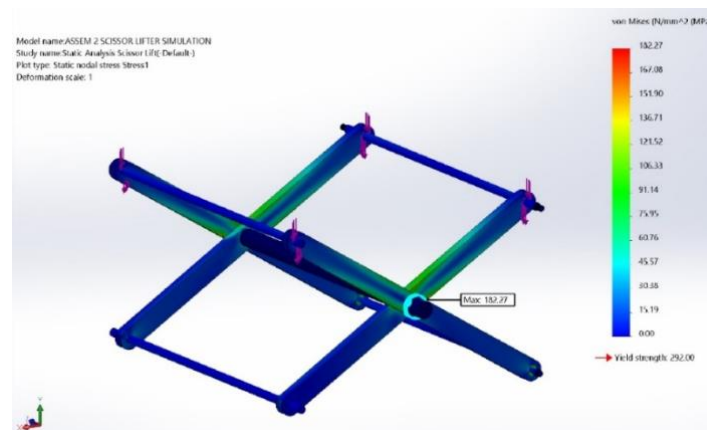


Figure 4.11 Scissor Lift Min Angle Stress Analysis

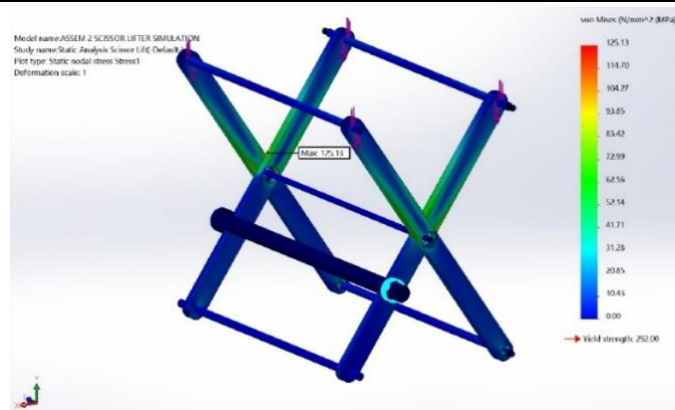


Figure 4.12 Scissor Lift Max Angle Stress Analysis

As shown in the Figure 4.30, the maximum von Mises value for the assembly when the angle is at the minimum and given a 100kg load is 182.27 MPa, while from Figure 4.31 for maximum angle the maximum von Mises value is 125.13 MPa. With yield strength equals to 292 MPa, the Factor of Safety for minimum angle is 1.55, whereas for maximum angle it is 2.33. The non-ideal conditions resulted in maximum displacement of 0.879mm when the load is focused on the front side (Appendix C, Figure C.2-C.3). As for the scaled-down scissor lifter, it resulted to only 1.0 FoS when given load of 120kg, but 1.7 FoS when given load of 70kg, this confirms the prototype's ability to stand load only up to 70kg (Appendix C, Figure C.4-C.7).

4.3.2 AMR Chassis

This chapter explains the validation of the main structures' mechanical design.

4.3.2.1 Base Plate

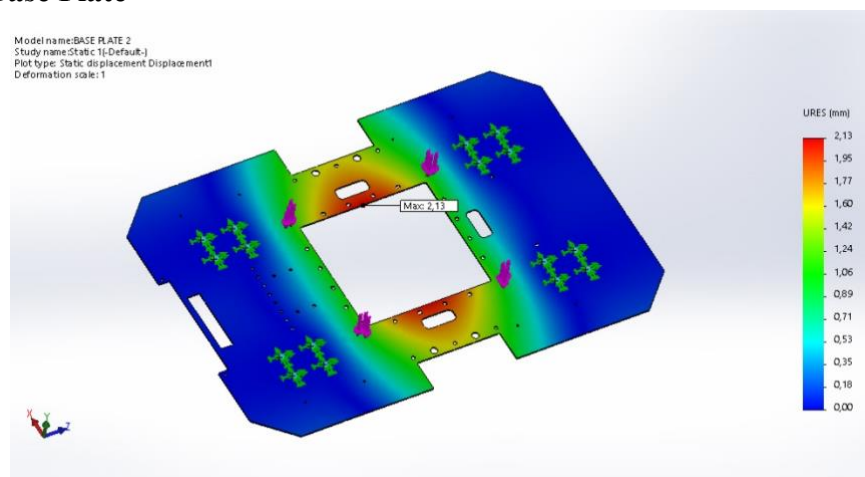


Figure 4.13 Base Plate Displacement Analysis

As shown in the Figure 4.39, the maximum displacement value for the assembly when given a 120kg load (100kg load + 20kg scissor lifter) is 2,13mm. The fixed supports are from the caster wheel mountings. The external load is from the scissor lifter bottom plate mounting. The maximum displacement happens on the left and right side of the base plate.

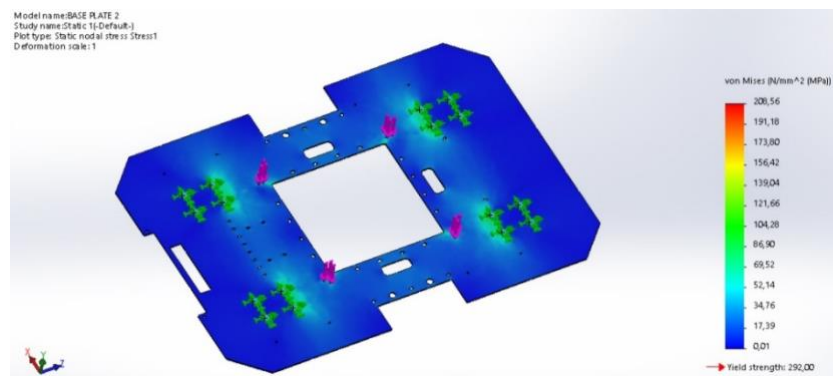


Figure 4.14 Base Plate Stress Analysis

The maximum von Mises value is 208,56 MPa, whereas the yield strength is 292 MPa. It will not break under the set load but it is very risky to use this as it is for the final product due to the Factor-of-Safety (FoS) being only 1,4 based on the failure stress and allowable stress.

$$F.S. = \frac{\sigma_{allow}}{\sigma_{fail}} = \frac{292 \text{ MPa}}{208,56 \text{ MPa}} = 1.4 \quad (4.1)$$

The minimum FoS should be in the range of 1,5-2. The base plate itself is not safe enough to hold this much weight. Therefore, a structural frame is needed for the AMR. Not just for the height, but also to increase the strength and load-bearing ability of the AMR.

4.3.2.2 Base Plate Welded with Hollow Steel Metal Frame

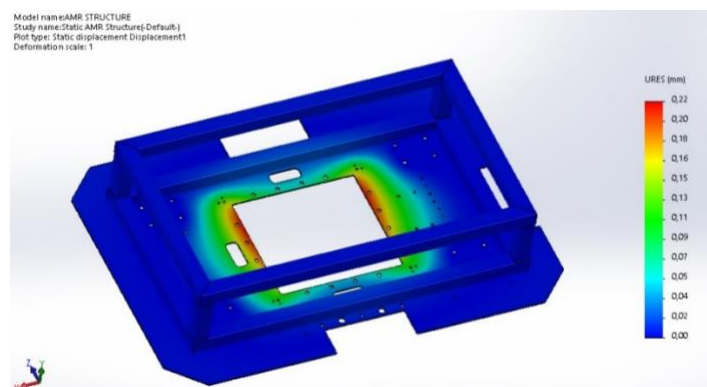


Figure 4.15 Base Plate with Hollow Steel Frame Displacement Analysis

After being welded with the hollow steel metal frame, the maximum displacement appears to be only 0,22mm, which is 9.7 times better than using only the base plate to hold the load.

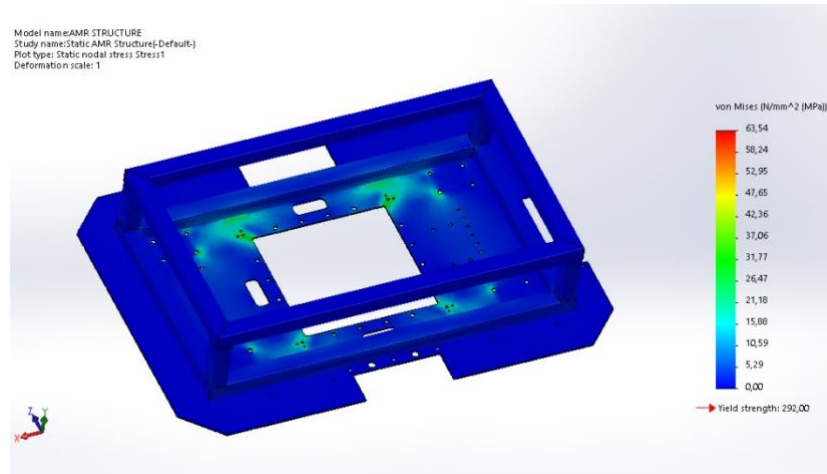


Figure 4.16 Base Plate with Hollow Steel Frame Stress Analysis

The maximum von Mises value is 63,54 MPa. This results in around 70% decrease in maximum stress compared to the base plate alone. This happens due to the stiffening after the two components are welded together. The hollow steel frame helped transformed the whole build and increase its entire area moment of inertia. The welded joint creates a fixed connection that forces the frame to absorb the internal bending moments in accordance with the formula $\sigma = \frac{Mc}{I}$, where σ is the stress which is directly proportional to M (bending moment) and c (distance), as well as I (moment of inertia).

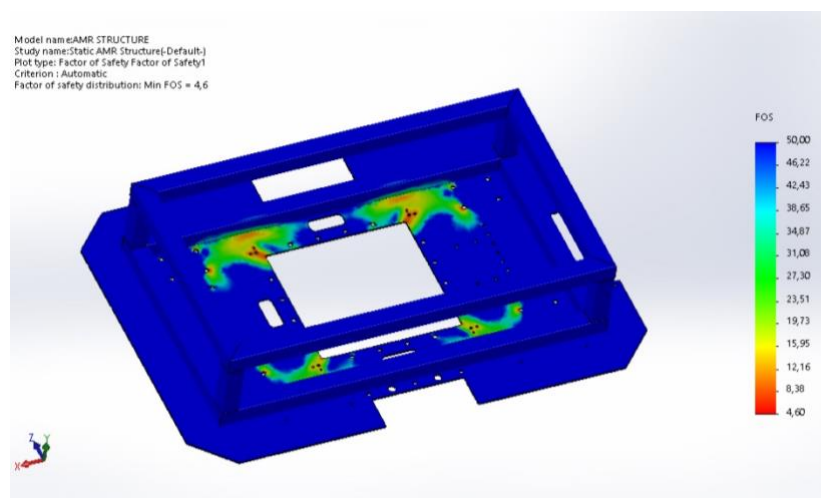


Figure 4.17 Base Plate with Hollow Steel Frame Factor-of-Safety Analysis

$$F.S. = \frac{\sigma_{allow}}{\sigma_{fail}} = \frac{292 \text{ MPa}}{63.54 \text{ MPa}} = 4,6 \quad (4.2)$$

The minimum FoS after welding the base plate with the hollow steel frame increases to 4,6 which is more than enough for an AMR. If the stress reduces, the FoS increases, they are inversely proportional with each other. Despite having the same dimension, the hollow steel frame shows better performance than the bent sheet metal frame because their fundamental design elements and material distribution methods differ. The hollow steel frame exists as a solid structure which maintains its complete form to deliver better torsional strength than typical bent sheet metal structure which have open designs. The system employs a continuous closed boundary combined with additional structural weight to block buckling at weld points which results in reduced base plate stress concentrations. The non-ideal condition analysis resulted in maximum displacement of 0.529mm when load is focused on the front side (Appendix C, Figure C.6-C.7).

4.3.2.2.1 Stiffness Calculation and Comparison

Based on the displacement analysis from both conditions, the stiffness can be calculated.

$$Stiffness (k) = \frac{Force (F)}{Displacement (\delta)} \left(\frac{N}{mm} \right) \quad (4.3)$$

With

$$Force = 120kg * 9,81kg \cdot \frac{m}{s^2} = 1177,2 \text{ N} \quad (4.4)$$

Therefore, the stiffness for the base plate only (k_0) is

$$k_0 = \frac{1177,2 \text{ N}}{2,13 \text{ mm}} = 552,6 \frac{N}{mm} \quad (4.5)$$

The stiffness for base plate welded with hollow steel frame (k_1) is

$$k_1 = \frac{1177,2 \text{ N}}{0,22 \text{ mm}} = 5350,9 \frac{N}{mm} \quad (4.6)$$

With all materials being 201 Stainless Steel, it can be concluded that welding hollow steel frame is almost 10 times stiffer than just the base plate alone and is valid.

4.3.3. Lifter Top Part

The top lifter part is made out of Bakelite material; this is the stress and displacement analysis of the part.

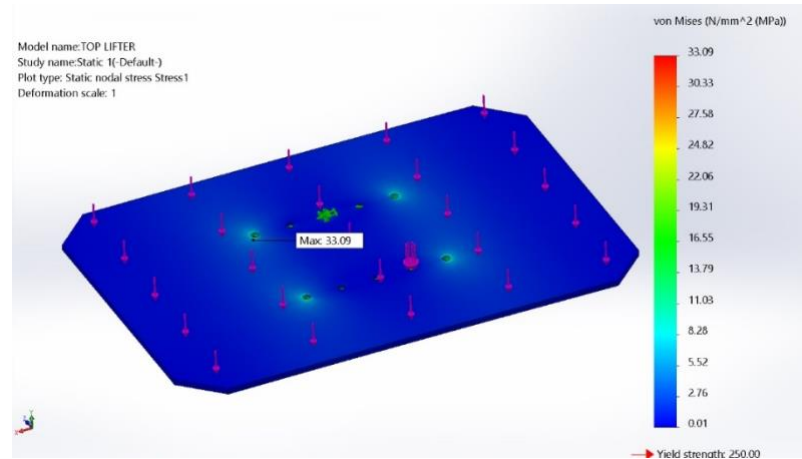


Figure 4.18 Top Lifter Stress Analysis

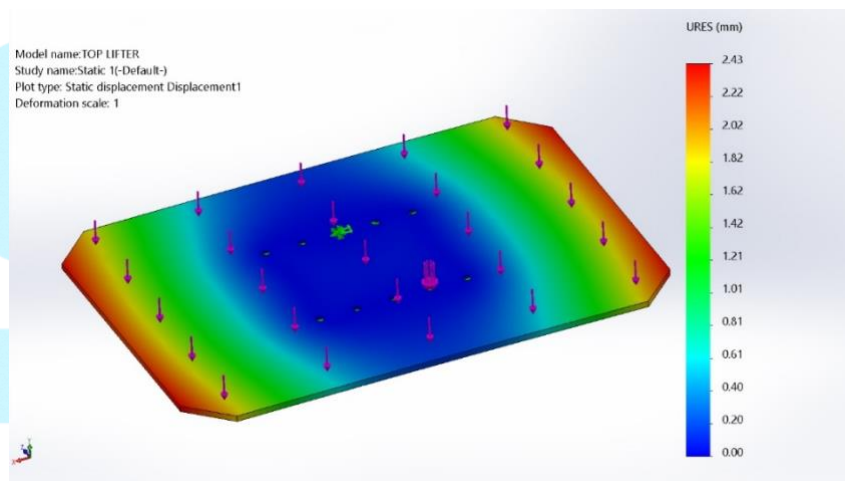


Figure 4.19 Top Lifter Displacement Analysis

The maximum von Mises value for this analysis is 33.09 MPa, while the yield strength is 250 MPa, which means that this part has a FoS of 7.5. This is considered as safe and well-designed. From the analysis, it is shown that the maximum displacement is 2.43 mm and at the very edge of the part. This is still under the limit hypothesized. The non-ideal condition analysis resulted in maximum displacement of 4.48mm when load is focused on the front side (Appendix C, Figure C.4-C.5).

4.4 Scissor Lift Prototype Test

From the design included in 4.1.1.4.2, the scissor lift parts are built and assembled with the specified stepper motor together with DM542 Stepper Motor Driver, which has

4.4.1 Scissor Lifter Prototype Assembly Result

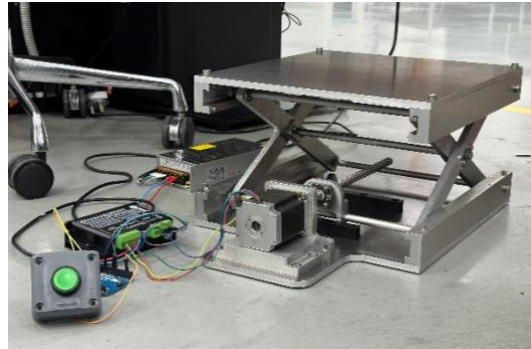


Figure 4.20 Scissor Lifter Prototype Minimum Lift Height

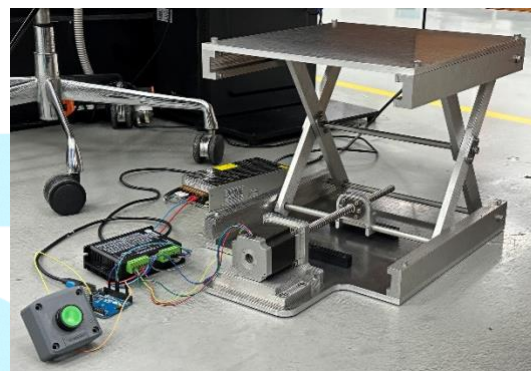


Figure 4.21 Scissor Lifter Prototype Maximum Lift Height

The scissor lifter prototype parts were fabricated in-house with CNC machines and turning machines for the shafts. The parts were built easily as the tolerances were already considered in the designing phase.



Figure 4.22 DM542 Stepper Driver

4.4.2 Scissor Lifter Prototype Test

The microcontroller used is Arduino UNO, this component is selected based on its availability and simplicity to use. It is used only to command the driver to go forward

or backward. A push button is connected to control the command. This scissor lift works well with weights under 75kg. It is proven by adding weights incrementally inside a plastic container. For context, the weighing machine has an initial offset of 6kg.



Figure 4.23 Weighing Machine



Figure 4.24 Load for Scissor Lifter Prototype Test

When the total load weight was 75kg, the shaft which is connected to the stepper motor bracket or the moving shaft bent as seen on the picture. The maximum rated load based on this testing is 70kg, where the shaft did not bend at all.

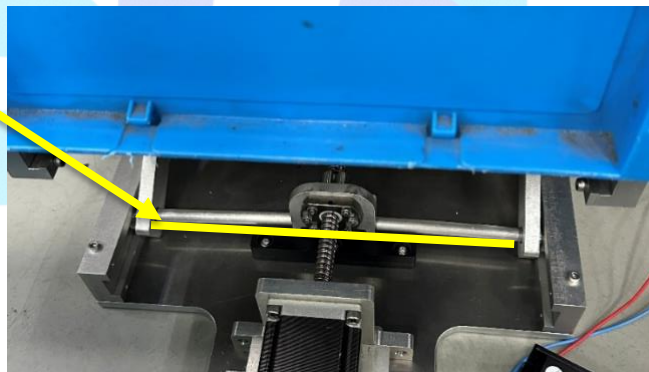


Figure 4.25 Moving Shaft Bent with 75kg Load

At lower angles, the force is significantly higher than higher angles, as established in the kinematic force analysis in 3.5.1.9.1. After this incident, the scissor lifter is moving more unstable. If there is no load, it lifts up the platform with good stability. When given 75kg load, it can lift but with unstable side-to-side movements. This is due to the moving shaft bending and therefore affecting the bearing positioning on the bearing base. The shaft is constrained only by the lead screw coupling and the bearing base, therefore subjected to a bending moment that exceeds the limit of the shaft material. This correlates with the 1.55 FoS at lower angle compared to 2.33 at higher angle analysis in 4.3.1.

4.4.3 Positioning Error Test Results

Table 4.1 Scissor Lifter Positioning Error Test Result

Scissor Lift Positioning Error Test					
Command Height (mm)	Initial Height (mm)	Increased Height (without load) (mm)	Increased Height (with load) (mm)	Positioning Error (mm)	Positioning Error (%)
10	207	217	216	1.00	103.86
20	207	227	227	0.00	109.66
30	207	237	237	0.00	114.49
40	207	246	246	0.00	118.84
50	207	257	255	2.00	122.22
60	207	267	267	0.00	128.99
70	207	276	276	0.00	133.33
80	207	287	287	0.00	138.65
90	207	297	295	2.00	141.55
100	207	307	305	2.00	146.38
103	207	310	309	1.00	148.79
Average Positioning Error				0.73	127.89

Based on the table, the average positioning error when given the load compared to no load is 1.74%, which in this case is very small. This good accuracy is due to the stepper motor and the ability to lift the load with 1.91A peak current / 1.36A RMS current and 1600 pulse/rev setting. From this testing, it can be concluded that using stepper motor as the primary actuator for scissor lift in an AMR is valid.

4.5 Positional Accuracy Test

The distance (x, y) used for this test is (1.5m, 1.5m). With the AMR dimension being (600 x 550) mm. The rqt graph shows the connection of the nodes and the publisher and subscriber connections (Appendix C, Figure C.8-C.11). There are tapes on the floor to mark the heading and positional destination point (Appendix C, Figure C.12-C.13).

4.5.1 LiDAR Merged Scan Accuracy

The LiDARs are merged using `ira_laser_tools`, which is already available for ROS Noetic. They are mounted diagonally and on top of the AMR. Based on the datasheet of both LiDAR types, the error should be under 1% of the actual distance if the distance

is below 3 meters. The LiDARs' scan gives the same error percentage result as the datasheet after being merged. The RViz measurement was done with the measure plugin.

Table 4.2 LiDAR Merged Accuracy Test

LiDAR Merged Accuracy Test (<3m)			
Measurements (mm)		Error (mm)	Error Percentage (%)
Physical	RViz		
3000	2989	11	0.367
2500	2493	7	0.280
2000	1988	12	0.600
1760	1764	4	0.227
1200	1208	8	0.667
400	396.6	3.4	0.850
500	499.3	0.7	0.140
375	373.3	1.7	0.453
360	358.9	1.1	0.306
Average Error		8.5	0.432

The mapping is done with this merged LiDAR scans. It was generated using the GMapping SLAM algorithm. The resulting map represents the walls and static obstacles of the workshop area. It will then be loaded to GMCL localization and used as reference map.



Figure 4.26 Mapping with Merged LiDAR Result

4.5.2 Full Fusion Positional Accuracy Test

Table 4.3 Full Fusion Physical Odometry Error Measurement

Physical Odometry Data						
Edge Gap X-1 (cm)	Edge Gap X-2 (cm)	Edge Gap Y-1 (cm)	Edge Gap Y-1 (cm)	X Error (cm)	Y Error (cm)	Total Euclidean Error (cm)
4.5	1	3.5	1	2.75	2.25	3.55
1.2	1.7	2.8	2.7	1.45	2.75	3.11
4.2	3.6	0.5	2.5	3.90	1.50	4.18
1.5	0.2	0.3	0.5	0.85	0.40	0.94
2.1	2.6	2.5	2.3	2.35	2.40	3.36
3.4	4.6	1.5	0.3	4.00	0.90	4.10
0.8	1.8	2	2	1.30	2.00	2.39
2.4	3	2.2	2.4	2.70	2.30	3.55
0	0.8	2.7	3.7	0.40	3.20	3.22
1.8	3.5	2.5	1.1	2.65	1.80	3.20
Average Error				2.24	1.95	3.16

Table 4.4 Full Fusion EKF Odometry Error Measurement

Sensor Fused Odometry Data		
EKF X (m)	EKF Y (m)	Total EKF Euclidean Error (cm)
1.523	1.564	4.33
1.479	1.534	2.78
1.495	1.535	2.03
1.498	1.591	4.67
1.523	1.576	4.98
1.441	1.584	7.12
1.469	1.511	2.07
1.497	1.536	1.92
1.443	1.584	7.09
1.465	1.541	3.79
Average Error		4.05

Table 4.5 Full Fusion Angular Error Measurement

Physical Angular Data			Sensor Fused Angular Data		
Angular X Error (°)	Angular Y Error (°)	Total Angular Error (°)	EKF Z (m)	EKF W (m)	EKF Yaw (°)
3.64	2.60	3.12	0.009	0.999	1.07
0.52	1.15	0.10	0.012	0.999	1.42
0.63	3.23	2.08	0.019	1.000	2.17
1.35	0.10	0.21	0.011	1.000	1.23
0.52	0.10	0.21	0.038	0.999	4.40
1.25	3.23	1.25	0.011	1.000	1.20
1.04	0.21	0.00	0.010	0.999	1.09
0.63	0.83	0.21	0.009	1.000	0.99
0.83	1.98	1.04	0.002	1.000	0.22
1.77	1.04	1.46	0.019	1.000	2.12
Average Error		0.97	Average Error		1.59

The parameters for this testing are xy_goal_tolerance and yaw_goal_tolerance being 0.075. The maximum velocity is 0.5 m/s. Combining LiDAR, encoder, and IMU achieved an average physical Euclidean positional error of 3.16 cm and an average physical angular error of 0.97°. The x-axis error (2.24cm) is slightly higher than the y-axis error (1.95cm), this suggests that the robot experiences positional deviation along the forward motion than the lateral axis.

The EKF odometry and angular data have greater error than the physical measurements. This happens due to the drift accumulation between GMCL correction cycles, while GMCL's particle filter continuously integrating the LiDAR scan matching to correct the robot pose estimation. The AMR was also able to move without any hiccups or problems. From the result, it can also be confirmed that the BNO055 IMU is providing stable orientation data with the angular error ranging from 0° - 3.12°. This test provides the valid and desired result to answer the third hypothesis of this thesis. With all the navigational components fused together, the positional error is 3.16cm.

4.5.3 Without LiDAR Positional Accuracy Test

Table 4.6 Without LiDAR Physical Odometry Error Measurement

Physical Odometry Data						
Edge Gap X-1 (cm)	Edge Gap X-2 (cm)	Edge Gap Y-1 (cm)	Edge Gap Y-1 (cm)	X Error (cm)	Y Error (cm)	Total Euclidean Error (cm)
3	4	12	6	3.50	9.00	9.66
5	2	12	6.8	3.50	9.40	10.03
1.5	4	11.6	6.8	2.75	9.20	9.60
6.5	10.3	7.3	4.1	8.40	5.70	10.15
2.8	2.5	12.3	6.8	2.65	9.55	9.91
4.8	1.8	9.2	3.3	3.30	6.25	7.07
2	4.4	11.3	6	3.20	8.65	9.22
0	6.4	9.3	4.4	3.20	6.85	7.56
0.4	5.2	10.8	5.4	2.80	8.10	8.57
3.8	3.5	12.3	5.8	3.65	9.05	9.76
Average Error				3.70	8.18	9.15

Table 4.7 Without LiDAR EKF Odometry Error Measurement

Sensor Fused Odometry Data		
EKF X (m)	EKF Y (m)	Total EKF Euclidean Error (cm)
1.488	1.473	1.93
1.452	1.492	2.78
1.481	1.491	1.42
1.456	1.477	3.36
1.481	1.489	1.51
1.485	1.531	2.29
1.478	1.502	1.21
1.475	1.496	1.43
1.489	1.487	1.21
1.479	1.503	1.21
Average Error		1.82

Table 4.8 Without LiDAR Angular Error Measurement

Physical Angular Data			Sensor Fused Angular Data		
Angular X Error (°)	Angular Y Error (°)	Total Angular Error (°)	EKF Z (m)	EKF W (m)	EKF Yaw (°)
1.04	6.23	6.31	0.059	0.999	6.71
3.12	10.30	10.77	0.058	0.998	6.60
2.60	7.87	8.29	0.054	0.999	6.23
3.95	3.12	5.04	0.058	0.998	6.67
0.31	10.10	10.11	0.055	0.998	6.30
3.12	7.66	8.27	0.061	0.998	6.97
2.50	7.15	7.57	0.059	0.998	6.74
6.64	3.02	7.29	0.060	0.998	6.91
4.99	5.81	7.66	0.054	0.999	6.16
0.31	9.09	9.10	0.059	0.998	6.77
Average Error		8.04	Average Error		6.61

The parameters for this testing are the same as the full fusion testing. Combining only encoder and IMU achieved an average physical Euclidean positional error of 9.15 cm, which is a 189.6% increase from full fusion configuration and also exceeded the `xy_goal_tolerance`. The EKF odometry and angular data have lower error than the physical measurements. This happens due to the EKF having no external reference to compare against, so it reports a confident estimation and states that it has reached the destination point, whereas in reality there are errors ranging from 7.07cm to 10.15cm. This also indicates that without LiDAR scan matching, the AMR loses its ability to correct lateral drift. The angular error degraded significantly from 0.97° to 8.04°, this confirms that without LiDAR providing global pose correction, the combination of encoder and IMU cannot maintain accurate heading.

Without any LiDAR scanning result, the AMR runs without any obstacle avoidance, therefore it runs on full speed (0.5m/s). This might also affect the inaccuracy of the position. This test provides the valid and desired result to answer the third hypothesis of this thesis. Without LiDAR, the positional error increases by 5.99cm.

4.5.4 Without Encoder Positional Accuracy Test

Table 4.9 Without Encoder Physical Odometry Error Measurement

Physical Odometry Data						
Edge Gap X-1 (cm)	Edge Gap X-2 (cm)	Edge Gap Y-1 (cm)	Edge Gap Y-1 (cm)	X Error (cm)	Y Error (cm)	Total Euclidean Error (cm)
3.6	4.6	16.3	18.4	4.10	17.35	17.83
3.2	6.3	21.8	26.8	4.75	24.30	24.76
1.3	4.5	28	23	2.90	25.50	25.66
6.8	4.5	5.7	19.9	5.65	12.80	13.99
2.8	1.5	5	20.3	2.15	12.65	12.83
11.7	14.5	13.5	17.5	13.10	15.50	20.29
0.5	1.8	22.3	26	1.15	24.15	24.18
0.2	2	21.8	25.4	1.10	23.60	23.63
1.4	5.5	7.4	25.8	3.45	16.60	16.95
4.6	2.2	20.3	28.2	3.40	24.25	24.49
Average Error				4.18	19.67	20.46

Table 4.10 Without Encoder EKF Odometry Error Measurement

Sensor Fused Odometry Data		
EKF X (m)	EKF Y (m)	Total EKF Euclidean Error (cm)
1.560	1.322	11.90
1.562	1.295	13.35
1.516	1.244	13.61
1.469	1.339	9.64
1.516	1.358	7.94
1.633	1.338	14.75
1.521	1.265	12.80
1.532	1.402	6.53
1.551	1.395	7.79
1.524	1.284	12.00
Average Error		10.93

Table 4.11 Without Encoder Angular Error Measurement

Physical Angular Data			Sensor Fused Angular Data		
Angular X Error (°)	Angular Y Error (°)	Total Angular Error (°)	EKF Z (m)	EKF W (m)	EKF Yaw (°)
1.04	2.19	1.61	0.032	0.999	3.70
3.23	15.74	5.19	0.014	1.000	1.57
3.33	23.14	5.19	0.004	1.000	0.41
2.39	1.25	14.48	0.045	0.999	5.15
1.35	3.64	15.55	0.013	1.000	1.51
2.91	1.04	4.16	0.170	0.986	19.52
1.35	20.44	3.85	0.034	0.999	3.87
1.87	19.80	3.74	0.046	0.999	5.25
4.26	1.98	18.50	0.051	0.999	5.85
2.50	18.22	8.17	0.049	0.999	5.61
Average Error		8.04	Average Error		5.24

The parameters for this testing are `xy_goal_tolerance` and `yaw_goal_tolerance` are 0.3. The reason for the increase of the goal tolerances are is due to the AMR keep reaching to 1.5m and 1.3m and keep going back and forth to go sideways, where it will never reach or in a long time. This concludes that the fusion of only LiDAR and IMU cannot consistently reach accuracy below 20cm. Combining only LiDAR and IMU, this configuration implemented `laser_scan_match` as its odometry data this method compares the robot position to the map to achieve the odometry. This configuration achieved an average physical Euclidean positional error of 20.46 cm, which is a 547.5% increase from full fusion configuration but still within the `xy_goal_tolerance`. The y-axis error (19.67cm) is significantly higher than the x-axis error (4.18cm), which could be interpreted that without encoder odometry, the AMR has no displacement or velocity estimate to feed into the EKF. Even the EKF data is worse than previous tests, meaning that the EKF data itself is degraded without encoder input. This test provides the valid and desired result to answer the third hypothesis of this thesis. Without encoder, the positional error increases by 17.3cm.

4.5.5 Without IMU Positional Accuracy Test

Table 4.12 Without IMU Physical Odometry Error Measurement

Physical Odometry Data						
Edge Gap X-1 (cm)	Edge Gap X-2 (cm)	Edge Gap Y-1 (cm)	Edge Gap Y-1 (cm)	X Error (cm)	Y Error (cm)	Total Euclidean Error (cm)
4	6.6	4.8	2.8	5.30	3.80	6.52
1	2.3	0.5	2	1.65	1.25	2.07
3.7	1.6	4.2	6.3	2.65	5.25	5.88
0.5	3.2	5.5	2.3	1.85	3.90	4.32
2.1	6.1	3.2	2.2	4.10	2.70	4.91
1.8	2.8	1.3	2.4	2.30	1.85	2.95
3.2	1.1	0.8	1.8	2.15	1.30	2.51
0.3	2.7	1.4	0.7	1.50	1.05	1.83
3.4	0.8	3.3	5.2	2.10	4.25	4.74
2.5	0.7	0.4	2.3	1.60	1.35	2.09
Average Error				2.52	2.67	3.78

Table 4.13 Without IMU EKF Odometry Error Measurement

Sensor Fused Odometry Data		
EKF X (m)	EKF Y (m)	Total EKF Euclidean Error (cm)
1.474	1.535	3.03
1.505	1.576	4.06
1.550	1.606	7.83
1.522	1.503	1.25
1.477	1.530	2.62
1.564	1.555	5.92
1.567	1.536	5.12
1.490	1.558	3.37
1.519	1.623	7.09
1.513	1.587	4.98
Average Error		4.69

Table 4.14 Without IMU Angular Error Measurement

Physical Angular Data			Sensor Fused Angular Data		
Angular X Error (°)	Angular Y Error (°)	Total Angular Error (°)	EKF Z (m)	EKF W (m)	EKF Yaw (°)
2.71	2.08	2.39	0.020	1.000	2.23
1.35	1.87	1.56	0.008	1.000	0.96
2.19	2.71	2.19	0.021	1.000	2.37
2.81	2.39	3.33	0.032	0.999	3.64
4.16	3.02	1.04	0.037	0.999	4.23
1.04	1.56	1.15	0.027	1.000	3.12
2.19	0.31	1.04	0.020	1.000	2.28
2.50	1.35	0.73	0.013	1.000	1.48
2.71	2.60	1.98	0.014	1.000	1.65
1.87	0.31	1.98	0.011	1.000	1.21
Average Error		1.74	Average Error		2.32

The parameters for this testing are the same as the full fusion testing. Combining only encoder and LiDAR achieved an average physical Euclidean positional error of 3.78 cm, which is a 19.6% increase from full fusion configuration and remaining inside the `xy_goal_tolerance`. The x-axis error and y-axis error are both relatively balanced, meaning that without IMU, the positional accuracy is slightly degraded but not critical. However, the angular error increased to 1.74°, resulted from the loss of BNO055's orientation contribution to the EKF. The EKF odometry error (4.69cm) is relatively comparable against full fusion EKF odometry error (4.05cm).

This indicates that without IMU data, the AMR running with GMCL can still localize and correct the pose estimation well. Excluding IMU does not critically impaired the whole navigation stack and positional accuracy. This test has proven part of the third hypothesis wrong. Without IMU, the positional error only increases by 0.62cm.

4.5.6 Statistical Analysis

To see the significance between full fusion and the three configurations, Paired Sample t-Test analysis is done.

Table 4.15 Paired Sample t-Test for Means

t-Test: Paired Two Sample for Means				
	<i>Full Fusion</i>	<i>Without LiDAR</i>	<i>Without Encoder</i>	<i>Without IMU</i>
Mean	3,16	9,15	20,46	3,78
Variance	0,87	1,15	22,77	2,92
Observations	10,00	10,00	10,00	10,00
df		9,00	9,00	9,00
t Stat		-11,07	-12,14	-1,07
P(T<=t) two-tail		0,0000015	0,0000007	0,3129574
t Critical two-tail		2,2621572	2,2621572	2,2621572

Table 4.16 RMSE Calculation

RMSE			
Full Fusion	Without LiDAR	Without Encoder	Without IMU
3.281	9.210	20.956	4.115

With a significance level (α) = 0.05 and degrees of freedom (df) = 9, it can be determined whether the removal of each navigational component produced a statistically significant change in average positional error compared to the full fusion as the baseline. The critical t-value for a two-tailed test at df = 9 is 2.262. Without LiDAR produces a t-statistic value of -11.07 with p value = 0,0000015 and without encoder produces a t-statistic value of -12.14 with p value = 0,0000007, both confirming significant degradation in positional accuracy at $p < 0.001$. However, without IMU produces a t-statistic value of -1.07 with p value = 0.313, which is below the critical value, which indicates no significant degradation in positional accuracy. The RMSE values of 9.21cm, 20.96cm, and 4.12cm further confirms these findings, concluding the inconsistency of positional degradation. These tests and analysis resulted to the conclusion that in this specific factory environment, the LiDAR and encoder fusion provides sufficient localization accuracy and that IMU's contribution does not generate significant improvement.