

CHAPTER 3 – RESEARCH METHODS

This chapter focuses on describing the methods to achieve the objectives of this thesis work. It includes the detailed conceptual structure, strategy and procedures for data collection, measurement and analysis.

3.1 Research Framework

The following flowchart outlines the entire research process, from initial problem definition to final conclusion, integrating the key phases of the operational design.

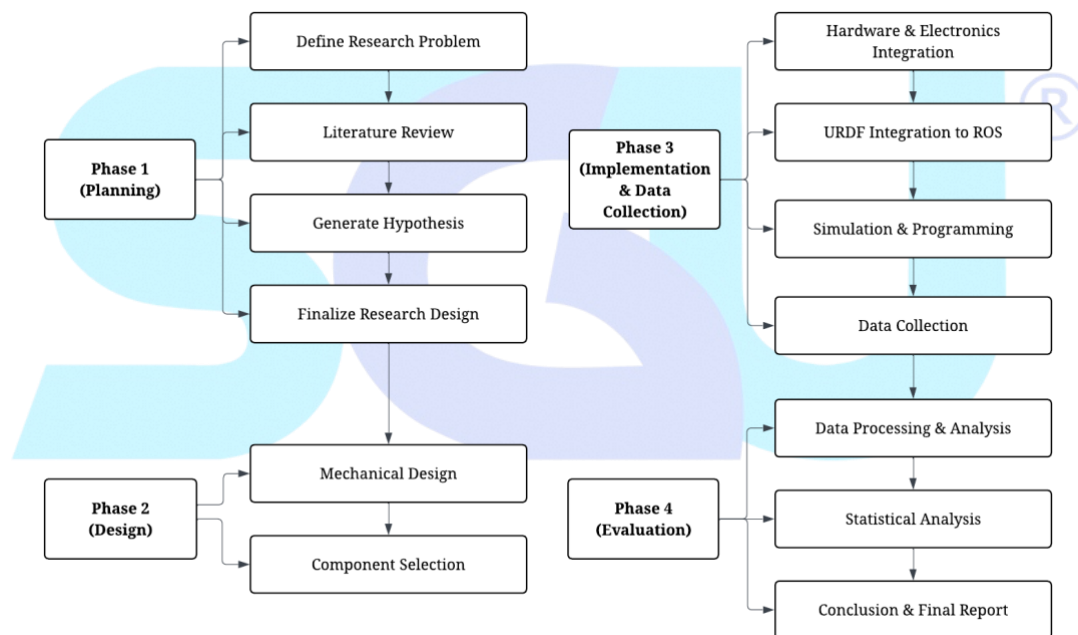


Figure 3.1 Research Flowchart

The research methodology is a structured process that consists of four phases. The first phase is the Planning Phase, where the research problem is defined, existing literature is reviewed, hypotheses are generated, and the study's design is finalized. The second phase, Design Phase, consists of setting up a baseline with the help of initial data collection, figuring out the technical specifications, and coordinating the decision of buying the needed hardware. The third stage, Implementation and Data Collection Phase, involves the integration of each sensor, the AMR's motion trajectories optimization, and installation and calibration of the mechanism to data collection. The

fourth phase, Evaluation Phase, includes through data processing and statistical analysis step by step, with the help of the Two-Sample F-test for instance, proving the system's performance, thus arriving at the final conclusion and report.

3.2 Research Design

The study adopts a Quantitative, Experimental approach, selected based on the primary objective requiring measurement, analysis, and validation of physical and simulated system. Using numerical data derived from mechanical calculations and simulations. This study focuses on three domains, mechanical structural integrity and/or machine design, lifting mechanism performance as well as autonomous navigation performance.

The mechanical domain will be done with a simulation-based experimental approach, where the AMR structure and scissor lift mechanism are designed using SolidWorks and simulated with the built-in FEA under defined load conditions.

The scissor lift performance is evaluated through direct physical measurement. The NEMA 34 Stepper Motor is actuated in 10mm height increments across the full stroke and actual platform height verified using a ruler. Positioning error is then determined by comparing measured height against the target at each increment. This data will produce a dataset that would reveal the correlation between lift height, power consumption, and positioning accuracy.

The navigation domain employs a sensor exclusion experiment, in which each sensor is individually disabled while the remaining sensors remain active, this is to quantify the contribution of each component for the positional accuracy. This experiment will be conducted using the company's existing hardware platform running ROS 2 with Nav2-based navigation stack and GMCL SLAM. Odometry data is recorded via the rosbag tool on the /odometry/filtered topic and compared with the physical measurement using the Euclidean calculation.

3.3 Data Collection Methods

The data collection process for this thesis work is divided into three parts, mechanical data and navigation odometry data. The data collection is conducted using a hybrid approach, combining digital telemetry and physical measurement.

3.3.1 Mechanical Data

To address the mechanical integrity of the AMR, only Finite Element Analysis method will be used, implementing software such as SolidWorks. The study will quantify the stiffness gains and vertical deflection under a 100kg load. A linear analysis will be performed to determine the critical load factors and ensure the design maintains a FoS above 2.0. The measurements will then be analyzed to check whether or not the design fits the requirement.

3.3.2 Scissor Lift Force Actuator Data

To address question 2, the NEMA 34 stepper motor starts from the starting angle position and move through 10mm increments. The actual for each step gets measured with a ruler and measurements get used to determine positioning error through comparison with the target height which results in a calculation error.

3.3.3 Navigation Odometry Data

The positional accuracy of each condition will be collected through two methods, digital telemetry via rostopic echo and physical measurement to ensure both the estimated and actual positions of the AMR are captured.

On the software side, the /odometry/filtered will be recorded for each trial. The topic publishes the robot's pose (x, y) and heading (θ) as the fusion between wheel encoder data and IMU orientation. Each trial is recorded corresponding to one of the four sensor configurations: full fusion, LiDAR disabled, encoder disabled, and IMU disabled.

Physically, the robot's pose will be measured using industrial tape measurement, with the origin (0,0) defined at the robot's starting position. There will be a tape on the ground to mark the edge of the AMR's body. The gaps from the AMR to the tape will then be calculated to get the Euclidean distance error between the robot's center and the origin.

3.4 Data Analysis Techniques

The research will utilize statistical analysis to provide an objective assessment of the hypothesis.

3.4.1 Statistical Analysis

Descriptive statistics will be calculated to provide a clear summary of the collected performance data. The Mean Absolute Error (MAE) (μ) will be determined to establish the average performance of each method.

To measure the error, the Euclidean Error formula is used.

$$E = \sqrt{(x_{target} - x_{measured})^2 + (y_{target} - y_{measured})^2} \quad (3.1)$$

At least 10 samples ($n = 10$) will be gathered to calculate the Mean Absolute Error. This is to measure how accurate the robot actually is.

$$MAE = \frac{1}{n} \sum_{i=1}^n E_i \quad (3.2)$$

Root Mean Squared Error will also be calculated to analyze the large deviations, this is crucial for AMRs or in the context of robotics.

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n E_i^2} \quad (3.3)$$

Another method is to calculate the error for X coordinates and Y coordinates separately. This is because differential drive robots often have different errors for forward motion (X) and rotational motion (Y).

3.4.2 Paired Sample t-Test Method

This method will be utilized to validate the navigation accuracy. It is selected because the odometry data and the physical measurements are dependent variables derived from the same events. By analyzing the mean of the differences between these paired observations, this test effectively isolates systematic calibration errors from random environmental noise. The method of calculation process is explained in chapter 2.2.8.

3.5 Required Materials and Equipment

To achieve the objectives of this research, there is some equipment needed. Software equipment is used to either design or simulate the AMR. Hardware equipment is integrated to produce the target AMR (Appendix A, Table A.1-A.2)

This subchapter includes the explanation as to why these components are required and why they are chosen for this thesis research.

Based on the LiDAR comparison from Table 2.2, Slamtec’s RPLiDAR S3 is selected for this research project due to its compatibility with the Mini PC and its cost-effectiveness. When compared to the alternatives like SICK TiM240 or the 3D volumetric sensors, this LiDAR offers 360° field of view with included support with ROS2. Its USB 3.0 interface and lower data complexity allows it to be the economical choice for this AMR (Slamtec, 2026).

Teensy 4.1 development board by PJRC, a 32-bit based ARM Cortex-M7 processor running at 600MHz. It offers 55 I/O pins and 35 PWM channels, ensuring all hardware can be interfaced directly to a single board. It features a floating-point unit (FPU) and 1024k of RAM. The built-in 480 Mbit/sec USB High-Speed port enables fast serial communication with the Mini PC. This microcontroller is used for low-level motor control, with integration via efficient communication for Micro-ROS, which is a proven method for control loop maintenance. This can also be used to integrate additional sensors in the future, such as ultrasonic sensors for safety usage. USB port and robust I/O from this microcontroller acts as the interface to bridge the gap between high-level navigation and physical execution. (PJRC, 2026).

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The Intel NUC (NUC13ANHi7) system delivers high-performance processing capabilities needed for real-time sensory data management and navigational algorithm operations. The system provides required computational power through its 13th gen Intel Core i7 processor and 16GB RAM and 512GB NVMe SSD configuration which enables low-latency ROS or ROS2 operation and complex path-planning activities. High level processing capabilities of the Intel NUC 13 pro makes it the suitable choice in terms of cost and suitability for the AMR's requirements. It enables the deep-stack software that allows the robot to make autonomous decisions. The PC specifications in AMR is very critical to cover the computational cost of the localization and navigation packages. The PC's compact design enables easy installation into the robot chassis (Intel, 2023).

3.5.1.4 ZLLG80ASM250-L V3.0



Figure 3.4 ZLLG80ASM250-L V3.0

ZLLG80ASM250-L V3.0 BLDC Motor is selected as the drive motor for this AMR. Pairing this motor, which has a diameter of 8 inches (210mm), it operates at 24 VDC with each delivering a rated power of 250W with a continuous torque of 8 Nm (peaking at 20 Nm), it is highly effective for transporting payloads up to 200kg. An important feature is the integrated 4096 high-resolution magnetic encoder, which is relatively accurate. This leads to the generation of noise-free odometry data, which is essential for precise localization within the ROS or ROS2 stack(ZLTECH, 2023a).

Based on the motor sizing calculations (Appendix B, Equations B.39-43), the required torque would be 6,26 Nm and the required power to run at 1m/s would be 62,6 W. This ZLTECH motor is selected for those specific requirements as it has a rated torque of 8 Nm and rated power of 250W.

3.5.1.5 ZLAC8015D



Figure 3.5 ZLAC8015D Motor Driver

ZLAC8015D Motor Driver is selected as it is a dual-channel digital servo driver capable of operating within 24V to 48V DC, supporting continuous current of 15A per channel. It utilizes an industrial RS485 / CAN Bus as a communication control method, allowing the Teensy 4.1 to send velocity commands and real-time telemetry. This driver supports operation nodes such as position control, velocity control and torque control (ZL TECH, 2023b).

3.5.1.6 BNO055 IMU

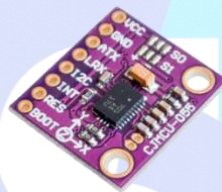


Figure 3.6 BNO055 IMU

This component is selected for this AMR due to its integrated architecture. It operates its complete 9-axis processing system to generate drift-compensated data which deliver precise time measurements while conventional IMUs need outside processing power to filter their unprocessed inertial measurement data. This enables ROS 2 ecosystem to function seamlessly because standard driver nodes (ros-imu-bno055) can directly connect the sensor output to sensor_msgs/imu messages. This enables GMCL localization to maintain accurate spatial transforms under conditions of magnetic interference and mechanical vibrations. IMU's ability to provide pose estimation and especially yaw headings ensure the system reliability in unpredictable factory floor dynamics. IMU can correct the wheel odometry drift and acts as additional information for the SLAM. (Bosch, no date).

3.5.1.7 Battery

To determine the power supply or in this case, a battery, the calculations are as follows.

3.5.1.7.1 Static Load

Power consumption for Intel NUC 13 Pro Mini PC Power is 45 W, RPLiDAR S3 is 2.5W and Teensy 4.1 is 1.5W. Therefore, the total power required for the static load is 5.39W and the static load is 54.39W (Appendix B, Equations B.1-B.2).

3.5.1.7.2 Dynamic Load

Assuming total mass is 140kg (100kg payload and 40kg chassis), the motorized wheel has an 8 Nm rated torque, 20 Nm peak torque, 6 A rated current, 18 A peak current. With a friction coefficient for TPU wheel on concrete $\mu_r = 0.08$, the rolling resistance force for steady-state cruising (constant velocity) would be 109.8 N. The required motor torque would be 4.75 Nm, from which the current drawn is 4.75 A. The power required is 114 W. Another case is when the AMR accelerates, the dynamic load would be greater due to the acceleration. Assuming the acceleration is $0.1m/s^2$, the acceleration force would be 14 N and the total force would now be 123.8 N. The torque required per motor would be 5.35 Nm and the current drawn during peak cruising would be 5.35 A. Therefore, the power required would be 128.5 W. (Appendix B, Equations B.5-B.13)

3.5.1.7.3 Battery Selection

Summing up the total current and power requirement for the AMR. The cruising current is 11.76 A and the power needed is 168.39 W. Whereas during peak condition, the current drawn is 17.8 A and the power needed is 182.89 W. Therefore, using a 60Ah battery would mean that the runtime of the fully charged battery during cruising would be 5.1 hours and 4.63 hours during acceleration. Assuming 30% being acceleration period and 70% is cruising period for the purpose of estimating average battery runtime in factory context, the current average would be 12.12 A and therefore the total runtime of this battery would be 4.95 hours. (Appendix B, Equations B.14-B.21)



Figure 3.7 LiFePO4 Battery

LiFePO4 24V 60Ah Battery Pack by ERA Battery, configured in a 4P8S cell arrangement. It provides a nominal voltage of 25.6V and includes BMS capable of delivering a continuous discharge of 60A and a peak current of 70A. Additionally, the

battery includes a CAN Bus communication interface, allowing for future integration for charging dock feature. It supplies a total energy capacity of 1.536 kWh, sufficient to sustain the AMR's operation for over 4 hours under a full 100kg payload. This fits into the general requirement of any industrial AMRs, where the general production shift hour is 8 hours, with an hour of break time.

3.5.1.8 C-CTEJ125-N Caster Wheel



Figure 3.8 C-CTEJ125-N Caster Wheel

The C-CTEJ125-N Caster Wheel is an industrial swivel caster specified for support substantial payloads, the 125mm wheel utilizes polyester as the fitting material. It provides support for 600 N up to 1600 N of allowable load. It acts as the passive stabilizing support that prevent the AMR from tipping over while also allowing multidirectional movement (Misumi, no date).

3.5.1.9 NEMA 34 Stepper Motor

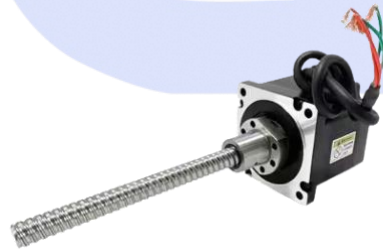


Figure 3.9 NEMA 34 Stepper Motor

The NEMA 34 Stepper Motor with this specific model number 34E30S6004B1N5-200RS operates with a rated current of 5.5A. It delivers a holding torque of 8Nm, providing sufficient force to lift the 100kg payload excluding the scissor lift structure itself. The integrated lead screw has a lead of 10mm and travel per step of 0.05mm at a 1.8° step angle, enabling high precision incremental height control (Oyostepper, no date).

3.5.1.9.1 Scissor Lift Actuator Calculation

Based on the free body diagram (Appendix C, Figure C.2-C.3) and the moments and force calculations (Appendix B, Equations B.22-B.38), the equation for force needed for this single stage scissor lift is

$$F_x = \frac{w}{\tan(\theta)} \quad (3.5)$$

Finding force and torque needed, with $W = 1070N$, $\theta_{start} = 30^\circ$, $\theta_{end} = 60^\circ$, lead $L = 10mm$, assumed efficiency (η) = 0.9, and FoS = 2.0

$$F_{start} = \frac{1070 N}{\tan(30^\circ)} = \frac{1070 N}{0.58} = 1844.8 N \quad (3.6)$$

$$F_{end} = \frac{1070 N}{\tan(60^\circ)} = \frac{1070 N}{1.73} = 618.5 N \quad (3.7)$$

$$\tau = \frac{F_{start} \cdot L}{2\pi \cdot \eta} = \frac{1844.8 \cdot 0.01}{2\pi \cdot 0.9} = 3.26 Nm \quad (3.8)$$

$$\tau_{ideal} = 3.26 Nm \cdot 2 = 6,52 Nm \quad (3.9)$$

With the ideal torque found, the force actuator required can be determined. Including FoS of 2.0, the ideal torque came up to be 6,52 Nm. The NEMA 34 stepper motor 34E30S6004B1N5-200RS was chosen based on this calculation.

3.5.1.10 ZED 2 Camera

Figure 3.10 ZED 2 Camera

The ZED 2 Stereo Vision Camera by Stereolabs serves as the primary perception system. An AMR needs to maintain continuous spatial awareness while it simultaneously detects obstacles. This camera uses a 6-Degree-of-Freedom visual-inertial stereo SLAM system which includes a built-in IMU, gyroscope, barometer, and magnetometer that function at 400Hz. This enables the camera to produce precise 3D point clouds while it moves through space. ZED 2 system offers a wide field of view which reaches 120 degrees and depth detection that extend from 0.3 meters to 20 meters (ZED, no date).