ELEC-E8111 Autonomous mobile robots, Design task 2024 Group C: Agricultural robot for harvesting olives.

Conceptual Work Report

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Requirements specification

1. Requires no or minimal human interaction (that includes the deployment phase).
Our system would require an initial setup, such as specifying the area where the robot is allowed to pick up olives since it is possible that there are neighbouring olive fields, and we don't want our robot to steal someone else's olives. In the initial setup, the user would also need to establish the connection with the robot and his own PC to establish the 5G connection to have the ability for remote control and possible exception state messages.

2. Be a cost-effective solution for development, operation, and maintenance.
A reasonable definition for low cost could be that our robot should not cost more than the salary(presumed to be 2 000€ a month) of 5 seasonal olive workers, and its maintenance costs should, on average, be ¼ the cost of a single seasonal olive worker. This would mean that if our robot can do the work of two olive pickers, it is reasonable since it can work anytime it is not recharging. This would mean that our robot would pay itself back in 3 years and, assuming a life span of 10 years, essentially triple the initial investment over ten years.

x = salary of an olive worker(which is 24 000€/year here), y=years. Here is a cost calculation assuming our robot is as effective as two workers.

$$\text{solve}\left(5\cdot x+\frac{1}{4}\cdot x\cdot y=2\cdot x\cdot y,y\right) \blacktriangleright y=2.85714$$

3. Operate with a solid commitment to environmental sustainability, minimising its environmental impact.
We aim for our robot's emissions to be as low as possible. It should handle the olive trees carefully to avoid breaking the branches. The choice of materials for the robot's manufacture should preferably be recyclable. The actuation system should give minimal stress to the plant and soil.

4. Plan according to the changing conditions.
Our robot is designed to adapt to changing conditions, such as sustaining some rainfall (up to 100mm a month). It is also programmed to react to the presence of humans working alongside it, ensuring their safety. This adaptability is a testament to the robot's versatility and reliability in real-world agricultural settings.

Hardware

We use the Lenovo ThinkCentre M70q Gen4 for computation. Its 90 watts of power consumption should be sufficient to implement SLAM and handle robotic arm computations.

Motor for our robot's locomotion. AYAZER 500W Brushless DC Motor 220V/2.8A Victory SC2-014 5000RPM BD-7&Grizzly G0765 Lathe Motor.

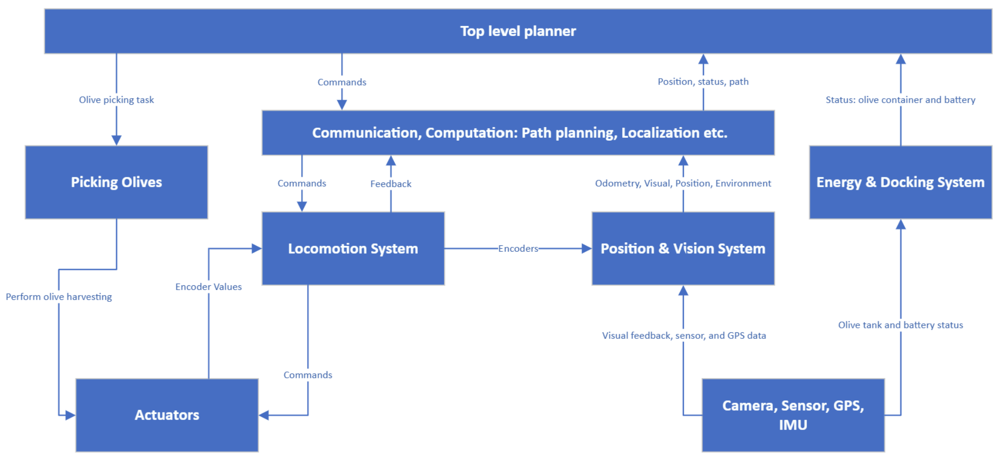
The energy density of a lithium-ion battery is 300 watthours per kilogram, so we need about 20 kg of batteries to have 6000 watts/hour.

Vehicle gross weight(maximum carry capacity, including the vehicle and trolley) 590 kg, Robot arm + gripper ~30 kg, vehicle 280 kg, rest(sensors etc.) ~20 kg, battery ~150 kg, i.e. 110 kg gross weight capacity(190 is carried already), i.e. this would preferably be towed.

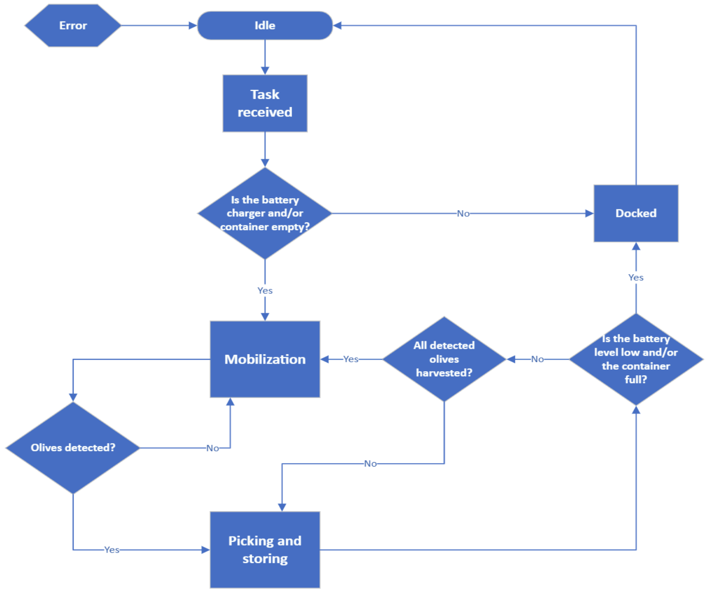
IMU: The Olive™ OLV™-IMU01-9D 310 €
GPS: Mosaic-X5(development kit) 1195 €
LIDAR: Husarion RPLIDAR S3   505 €
Camera: Stereolabs ZED X Stereo Camera. 599,00 €
Computer: Lenovo ThinkCentre M70q Gen4 969€
5G antenna: USB 5G antenna 15 €
Locomotion: tires, motors and actuators 3398 € + estimate of suspension and chassis 800 €
Robotic arm: total 4000 €
Battery: 450Ah 24V LiFePO4 Deep Cycle 24450L Battery 5122€
Total cost: 16 913 €

High-level description

System Diagram



Control Flow



When designing the olive-picking robot, it is essential to consider all its operational states. The robot has been designed to function in different states and carry out its tasks efficiently.

The robot's initial state is idle, during which it awaits tasks while checking its battery and the status of the olive container. The robot transitions to the docked state if the battery is low or the container is complete. While docked, the robot charges its battery and empties the container. Additionally, it continuously checks for tasks, and once the battery is sufficiently charged and the container is empty, it moves to the mobilisation state to begin moving.

Upon detecting an area with olives, the robot moves to the location and initiates the olive-picking process. Throughout this process, it continuously monitors the battery and container levels and the completion of tasks. If the battery is low or the container is complete, the robot returns to the docking state to recharge and empty the container. Furthermore, if all the olive trees have been covered and no more olives are detected, the robot returns to the dock to await new tasks.

It is important to note that the robot can encounter errors in any state, which must be resolved before it can resume normal operations.

Subsystem Description

I. Energy and Docking System

For the robot to harvest olives efficiently, it needs a sufficient power source to power the moving platform, robot arm, processing unit, and sensors. The power source in the robot shall be a battery system that powers all the necessary equipment on the robot. The robot has the following power requirements:

1. The AVG energy system platform, including the trolley, shall have a configuration similar to that of the Warthog unmanned ground vehicle (UVG) by Clearpath Robotics. Our UVG uses of power are 12 V, 24 V, and 48 V. fused at 10 A. This gives a total of 120 - 480W for the AVG platform. [1]
2. The robot arm shall have a similar configuration to Universal Robots' UR5e. Our robot arm

requires a 12/24 V power supply voltage and consumes between 350W and 700W. [2]

3. Sensors and Measurement Units:
    - Mosaic-X5 power requirement is 1W
    - IMU power requirement is 1.5W
    - Husarion RPLIDAR S3's power requirement is 3W
    - Stereolabs ZED X Stereo Camera power requirement is 3W
    - Husarion RPLIDAR S3 power requirement is 3W
4. Processing Unit
    - Lenovo ThinkCentre M70q Gen4 power requirement is 90W

Overall System Requirement

We consider the overall system's minimum and optimal power consumption requirement values.

Total Power Consumption (P) = AVG Platform (Min/Max) including trolley + Robot Arm (Min/Max) + Mosaic-X5 + IMU + Husarion + Occam Omni 60 + RPLIDAR S3 + Lenovo ThinkCentre M70q Gen4

Total power consumption, minimum = 120W + 350W + 1W + 1.5W + 3W + 3W + 3W + 90W = **571.5W.** Optimal power consumption = 480W + 700W +1W +1.5W +3W + 3W + 3W + 90W = **1281.5W.** Therefore, the robot needs at least 571.5W to operate, but we will target the optimal power requirement for optimum performance.

Battery capacity

The battery shall have a minimum capacity of 5126 Wh (214 - 427 Ah) for 4-hour optimum operation. To account for conversion losses due to factors like voltage regulation, 5-20% of buffer shall be added to ensure sufficient operating time. This translates to the final capacity of **224Ah—513Ah**.

A few battery options meet these requirements in the market:

1. **450Ah 24V LiFePO4 Deep Cycle 24450L Battery [3] $5,559.00**
2. 24V 450AH Intelligent Lithium Iron Phosphate Battery [4] $5,599.00
3. SOK 206Ah | 12V - Heated LiFePO4 Lithium Battery [5] $1,275.00
4. SOK Battery 12V 206Ah Heated LiFePO4 Metal Box SK12V206H [6] $1,206

We will choose option 1(boldened) for our robot implementation.

Charging and docking

The docking and charging subsystem is a crucial component of the robot system, and it is responsible for initiating the automatic docking process of the robot whenever alerts regarding low battery levels or a full olive container are received. The purpose of this subsystem is to simultaneously charge and offload olives, given that the robot docking is implemented correctly. The subsystem shall receive battery/container level alerts as inputs from the sensors and outputs a status for the top-level planners.

The docking process involves two main aspects: navigation and the docking algorithm. Navigation consists of the localisation and path planning subsystems, which navigate the robot to the dock. On the other hand, the docking algorithm utilises features obtained from the perception subsystem to acquire and maintain alignment with the station throughout the entire sequence.

Various methods exist for aligning the robot using visual perception. A recommended method involves using light or infrared emitters from the dock, which the robot can apply to sense its orientation relative to it. However, the most convenient way to achieve alignment involves using visual markers placed on the dock as landmarks for relative orientation, utilising the robot's depth cameras. Physical guides are suggested to help maintain alignment during the sequence, which is relatively inexpensive and easy to implement. These guides effectively prevent the robot's misalignment and ensure proper attachment.

One potential charging station option is Delta-Q IC650 battery chargers [7]. This option shall be considered in the design of the docking and charging subsystem. The use of Delta-Q IC650 battery chargers will not only ensure efficient charging but also increase the lifespan of the robot's battery. Using this charger, the charge time is with a minimum capacity of ~7h (4602Wh /650W). This would give the system two 4h working periods (i.e. 8h) within 24h.

II. Locomotion System

Wheel configuration

The larger wheels are suitable for hilly terrain and obstacles. Pneumatic Tires are better at absorbing shocks than solid ones. For the tread pattern, we need to choose one that provides less impact on the soil and has a good grip. BKT Agrimax Tire 250/85R24 109A8 [8] as an agricultural-use tire is suitable. This configuration ensures the robot can navigate agricultural landscapes with the least harm to the soil structure. The large size and specific tread design also enhance the robot's ability to overcome physical obstacles and maintain stability on uneven ground.

Drive system

A four-wheel-driven (4WD) configuration equips each wheel with high-torque brushless DC motors, such as the Maxon EC-i 40 High Torque Motor [9]. This setup provides sufficient power and traction for uneven and sloped terrains. The 4WD system ensures traction in various terrain conditions, essential for the robot to perform its tasks reliably in a dynamic outdoor environment. The high torque output from each motor allows the robot to navigate slopes and obstacles, ensuring consistent performance.

Steering mechanism

A 4-wheel steering(4WS) system is adopted for moving carefully between the olive trees. Both steerable front and rear wheels reduce the turning radius. 2 actuators are used, one for the front axle and one for the back axle. By reducing the turning radius, the robot can navigate more efficiently, minimising the risk of damaging plants or the robot itself. This system allows the robot to perform tasks more effectively, optimising the harvesting process and reducing time and energy consumption. The Dynamixel XM430-W350 actuator [10] is chosen due to its high torque and high-resolution feedback.

Suspension system

Independent suspension allows each wheel to react independently to the terrain. This setup reduces the impact on the robot structure while facing bumps and protects the sensitivity of sensors and actuators. This is essential for accurate sensor readings and effective operation. It also minimises the impact on the robot’s structure and sensitive components, enhancing durability and operational reliability.

Control system

Model Predictive Control(MPC) is adopted. MPC considers the dynamic interaction between the robot and the environment, predicts the future states and optimises the control input. It can handle changing environments such as uneven terrain and obstacles. The control system integrates sensors, actuators, and controllers. It takes real-time feedback from wheel encoders, GPS, and IMUs to adjust the motor outputs for speed and directional control. Each Maxon EC-i 40 High Torque Motor has a Maxon motor controller. Sensors should include GPS, IMUs, and incremental encoders for wheels.

III. Positioning system, Vision system

The positioning and environmental awareness system comprises four parts to meet the specifications:

- GPS is used for large-scale positions, e.g., where the system is located within the farm.
- LIDAR is used for tree and other obstacle detection, i.e., environmental mapping.
- The camera is to work with LIDAR in environment mapping and olive and ripeness detection.
- IMU for inertial measurements, i.e. where the system is located.

IMU:

- The Olive™ OLV™-IMU01-9D[11] is chosen because it is relatively cheap, high-quality, and ROS2 compatible.

GPS:

- Once again, Mosaic-X5(development kit)[12] is chosen for GPS due to its quality, connectivity, and compatibility.

LIDAR:

- Husarion RPLIDAR S3 [13] is chosen as LIDAR due to the price competitive option and 360 view.

Camera:

- Stereolabs ZED X Stereo Camera [14] as this camera is relatively economical, has depth vision(can form point clouds with computation aid) and has IP67 protection.[15]This camera is integrated into the robot hand and thus works for obstacle detection/mapping and olive/olive ripeness detection.

IV. Electric Lift actuation, Robotic arm

The robotic arm, which is in charge of the actual procedure of harvesting olives, is among the essential subsystems that impact the overall olive-picking efficacy. This subsystem includes the robotic arm and its operation, the gripper mechanism, and the end-effector, which eliminates the olives from the branches. In other words, everything associated with the procedure of the effectiveness and efficacy of the robotic arm is thoroughly covered here.

Robotic Arm Design

The robotic arm is developed with 7 degrees of freedom to allow more flexibility and accuracy when moving on the branches and touching the olives. Indeed, the seventh degree of freedom is necessary because it enables the robot to move independently, prevent different obstacles, and take olives from multiple angles without getting stuck or having a locked gimbal. This is the best arrangement as the robot arm is similar to the human arm in meeting the requirements.

Components and Specifications

- **Actuators:** The robotic arm is sculpted using a duality of rotations: rotary actuators, extensions, and linear actuators. The rotary actuators deliver rotation at each joint. On the other hand, linear actuators extend or retract to the varied length of the arm.
- **Motor:** The Dynamixel XM430-W350 actuator was chosen for its high torque development, precision, lights, and durability. In addition, it can be controlled programmatically and is the default actuator in several robotic machines due to its reliability.
- **Material:** The arm materials, carbon fibre and aluminium alloy, were selected to lower weight and maintain integrity. The approximate price is ~100€.
- **Power:** The actuator operates at 24 Volts and consumes an average of 50 Watts, and during more demanding operations, it can consume a peak of 100 Watts.

The total of this system would be approximately ~4000€, with an assumed 20% additional unexpected cost.

Gripper Mechanism

This mechanism has two independent prismatic joints and one combined revolute joint. Two prismatic joints are mainly employed for opening and closing, and a single revolute joint is used for the rotational adjustment of the olives' grip position. Two jaw prismatic joints allow proper location adjustment and facilitate the olives' soft silicone-coated fingers' grip. Integrated force sensors control the proper grip power dynamically.

Suction Mechanism

In addition, the robotic arm has a suction system that helps to pick the olives from the end-effector and transport them to the trolley. The suction system comprises a vacuum pump, suctional pipes, and a sorting mechanism installed in the trolley. It was established that a high-efficiency vacuum pump such as the Gast Vacuum Pump generates suction. The pump operates on a voltage of 24V, accompanied by a power consumption of about 100W. The vacuum pump is linked to the Picker and trolley by suction pipes. It was decided to use flexible, rigid suction pipes, which are very easy to use to run the olives from the grove to the sorting tray without destroying them in the garden. There are also sensors to assess the status or quality of the identified olives when the olives reach the trolley.

Control and Actuation

The control system relies on sophisticated algorithms to orchestrate the actions of the robotic arm and the gripper. Model Predictive Control is responsible for the dynamic interplay of the robot with its surroundings, predicting future states and optimising the control inputs. Additionally, the kinematics of the arm's movement is that of a linkage problem and can be modelled with Denavit-Hartenberg parameters. Consequently, joint positions and movement may be calculated with precision. Here, θi is the joint angle, αi is the link length, di is the link offset, and αi is the twist angle.

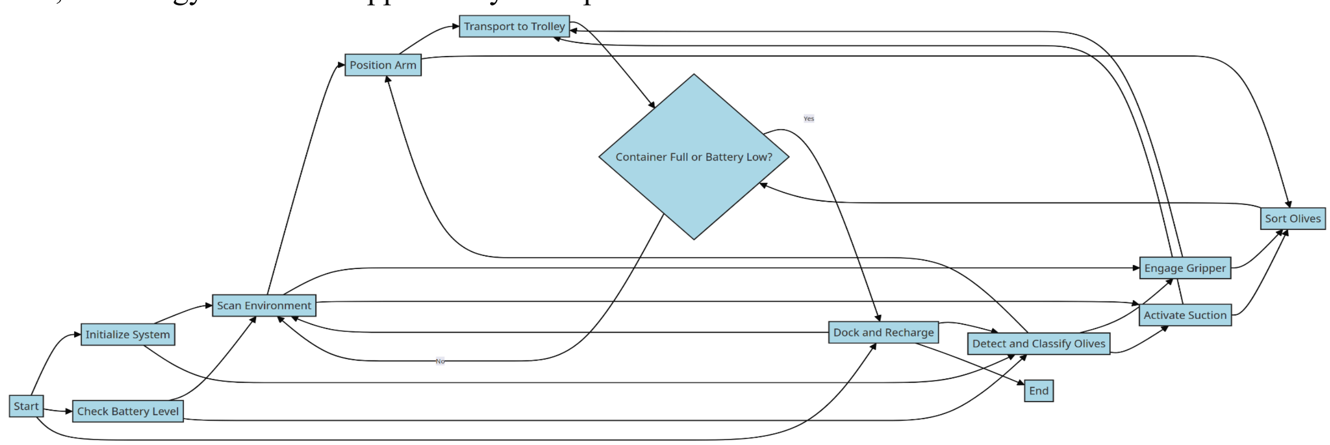
$$
\boldsymbol{T}_i = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\sin(\alpha_i) & a_i\sin(\theta_i) \\ 0 & \sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

Dynamic Equations: The dynamics of the arm are governed by the Euler-Lagrange equation. Where $L=K-P$ is the Lagrangian, K is the kinetic energy, P is the potential energy, q are the joint coordinates, and τ are the joint torques.

$$
\frac{d}{dt}\left(\frac{\partial L}{\partial q}\right) - \frac{\partial L}{\partial q} = \tau
$$

Power Consumption and Energy Efficiency

Additionally, the energy consumption of the robotic arm is controlled as optimally as possible based on the available system. The work process records the amount of power consumed per actuator, and reduction algorithms are used. In this case, the average power consumption of a robotic arm is about 350W, while during intensive work, the indicator increased to 700W. The battery system was expected to cover the total power needs and allow the robot to work continuously during the day. The rest of the time, the energy would be supported by solar panels.



Sorting Mechanism

After the olives are harvested, they are flown into the trolley using the suction pipes, and the trolley sorts them depending on whether they are of high or low quality. Since the flying olives pass through the suction pipes into the trolley, optical sensors and the trolley's position detect these. Some actuators cause the trolley to tilt on one side or the other, depending on whether an olive is good. These actuators are controlled by the central processing unit, which receives the data from the sensors.

V. Computation and Communication

For the computation, we are using Lenovo ThinkCentre M70q Gen4. This PC is powerful enough to perform sensor fusion, compute the algorithms that our robot needs, such as SLAM, and run the

reinforcement learning program of the robotic arm. Reinforcement learning is a technique where we have a state space of the robotic arm and a reward function that rewards beneficial actions. Then, this information is used to create a policy that will choose the action it thinks is the best based on the expected rewards. We must use policy gradient methods because our robotic arm has a continuous state space. Some policy gradient methods are PPO (proximal policy optimisation) and REINFORCE. We will choose PPO because it is more sample efficient, and training the PPO is more stable. PPO achieves more stability by clipping, which caps how much the current learned policy can change in each iteration. In this context, policy is a mapping from state to action that maximises the reward.
For computer vision, we will use a BLOB filter to detect olives. The blob filter works by convolving different sizes of blobs through the images taken by the camera. This should give a solid response to the olives as they are pretty circular objects with slightly different colours, so when the blob filter is on top of the olive, and the size of the blob matches the size of the olive, we get a strong response thus getting a match for a potential olive. After running the blob filter and finding some olives and other things that respond strongly to the blob filter, we will put the different BLOBs into an image classifier that should first recognise whether the blob is an olive and then whether the olive is ripe. This could be done using two CNNs:s (Convolutional neural networks). Then, once we have detected the ripe olives, we will stitch together the pictures taken by both cameras so we can use triangulation and the knowledge of where our cameras are to detect the location of the olive and give this information to the PPO algorithm, which should then have the ability to pick up the olive. Our robot could also be controlled remotely via 5G. Still, the robot must be updated via the PC for more considerable modifications, such as updating the code. The 5G will also alert the olive farmer about possible exception states the robot might enter, such as if it somehow flips itself over or gets stuck.

Analysis of constraints and weaknesses

First, it is essential to point out that our olive-detecting robot operates in an open field and relies on computer vision to detect the olives. The robot is constrained by the impossibility of operating at night and battery life. The robot has a battery capacity of about four hours and takes the same time to charge. This means that the difference in the work capacity for the robot is about 50%. To be efficient, the machine should consume the power from a full battery when it starts the day and leave it with a little charge; it should avoid the charge from the source during the day. The battery charges the machine faster at 80%, and regular batteries should only go to about 80%. The limitation means that the battery should charge quickly and not be depleted to prevent the machine from shutting down due to a lack of power.

Second, the power supply has to be consistent with the voltage supply to the different parts of the machine, such as the 12V, 24V, and 48V, without a significant voltage drop. The only mode of recharging will be the charging and docking state. Thus, even with more than one robot deployed at work, recharging might take time, leading to increased downtime. Moreover, the batteries and systems are much more complex, heavy, and expensive in practical application. Finally, the robot's energy is limited because it needs large and high-capacity batteries, which weigh much, cost much, and charge much for a long time. The limitations in energy hinder the operational effectiveness and increase the complexity of the energy system. Solving these problems will be addressed by enhancing the battery usage efficiency or changing the vehicle dynamics. The economic factors that don't have to be enhanced are the battery's lifetime and technical support, which significantly add to the lifetime cost of the operating system and alter the system's economics.

Another constraint to be addressed is the computer vision algorithm. In reality, even if our image classifier for detecting ripe olives is not 100% accurate, it will also pick some unripe olives. Or, in the worst case, it will pick some other stuff, such as olives that are not. However, it can sometimes find weird ways of maximising the reward function. The problem is that all the stuff our robot picks must be ripe olives.

Reference

[1] Warthog Unmanned Ground Vehicle Robot - Clearpath (clearpathrobotics.com)
[2] UR5e Lightweight, versatile cobot (universal-robots.com)
[3] MillerTech 450Ah 24V PREMIUM Lithium Iron Phosphate (LiFePO4) Smart Ba – LDSreliance
[4] 24V 450AH Intelligent Lithium Iron Phosphate Battery - Miller Tech (millertechenergy.com)
[5] SOK 206Ah | 12V - Heated LiFePO4 Lithium Battery – Curious Campervans
[6] Amazon.com: SOK Battery 12V 206Ah Heated LiFePO4 Metal Box SK12V206H : Automotive
[7]clearpath_robotics_016519-TDS1-ed6016c7d487e9b23cad0dca6e8abd7e.pdf (clearpathrobotics.com)
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[15] https://alcom.be/uploads/zed-x-datasheet-march-2023.pdf