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Luis Emiliano Rodrıguez Raygoza, Allen Uriel Barragan Hernandez, Luis Carlos Felix Herran, Jorge De-Jesus Lozoya-Santos, Juan C. Tudon-Martinez, et al.. Power Consumption Profile of a Service Robot: Characterization and Analysis. ISEM 2023 - 2nd International Symposium on Electromobility, Oct 2023, Monterrey (Mexique), Mexico. ⟨hal-04238496⟩

HAL Id: hal-04238496

https://hal.univ-grenoble-alpes.fr/hal-04238496v1

Submitted on 12 Oct 2023

Power Consumption Profile of a Service Robot: Characterization and Analysis

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***Abstract*—This paper presents a comprehensive analysis of the power consumption characteristics of an autonomous service robot across different operational scenarios. The study investigates the discharging profile of a 14.8V 4-cell 10,000mAh LiPo battery, providing insightful observations on the relationship between the State of Charge (SOC) and internal resistance, alongside voltage dynamics during discharge. The results indicate an inverse relationship between the SOC and the system's internal resistance, and a consistent voltage decrement corresponding to SOC. Furthermore, the energetic impacts of various robot components during the Powering On Procedure and Teleoperation and Navigating Procedure are detailed, identifying critical components contributing to high energy consumption. The paper suggests an autonomy duration of approximately 3.5 hours for the electrical system and 2 hours of continuous movement. The study provides a basis for optimizing energy efficiency in autonomous service robots.**

***Index Terms*—Power consumption profile, Service robots, State of Charge, Discharge battery profile**

I. INTRODUCTION

With the rapid advancements in robotics systems and the integration of artificial intelligence, today's robotics systems have become increasingly capable of delivering a diverse range of services with enhanced productivity and efficiency [1]. These advancements in robotics technology have led to the emergence of a new category of robots known as service robots. These service robots are specifically designed to autonomously assist humans in key sectors and are currently employed in transportation, hospitality, medical, cleaning, and agricultural applications [2].

In accordance with the International Organization for Standardization (ISO 8373), a *service robot* is defined as a robot employed in personal or professional environments to carry out practical tasks for the benefit of humans or equipment. The ISO standard further emphasizes the importance of a degree of autonomy in service robots, referring to their ability to execute intended tasks based on their current state and sensing capabilities without requiring direct human intervention [2].

Energy limitations pose significant challenges for mobile robotics. While motion planning is often the focus of existing studies to reduce power consumption, it is essential to recognize that motion is not the sole power consumer [3]. Understanding the energy consumption and efficiency of service robots is crucial for optimizing performance, managing battery usage, and comprehending the impact of different technologies and components on operational duration. In this context, this research aims to address these challenges by presenting the procedures and results of a comprehensive battery and power consumption profile study conducted on PiBot (shown in Fig. 1), a service robot developed by Tecnológico de Monterrey as a research platform [4].

In this study, key actions, such as powering electronics, activating the main computer, and executing autonomous navigation tasks, are carefully observed and analyzed to determine their effects on power consumption. This examination significantly contributes to the field by providing a holistic analysis of power consumption in service robots, an area that has received limited attention in previous research. Moreover, the study includes a battery profile analysis using a widely accessible and extensively utilized battery from a reputable brand, ensuring practical relevance and applicability to real-world scenarios. By considering the broader scope of power consumption beyond motion, this research provides valuable insights for energy-efficient designs in service robotics.

This paper is organized as follows: Section II presents the service robot system, including its components and batteries, as well as the analysis system employed. The battery profile methodology and power consumption methodology for both the motors and electronics are described in detail. In Section III, the experimental results obtained from the battery profile study and power consumption analysis are discussed. The findings and their implications are examined in depth. Finally,

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Fig. 1. PiBot: Service Robot and research platform from Tecnológico de Monterrey

Section IV provides the conclusions drawn from the study, along with potential directions for future research.

II. MATERIALS AND METHODS

The Materials and Methods section of this manuscript outlines the methodologies employed to study the power consumption behavior of the PiBot autonomous service robot. The experimental setup involved the utilization of the PiBot platform, which runs on Ubuntu 18.04 and the Robot Operating System (ROS) Melodic, and relies on Turnigy 14.8V, 4 cells, 10,000 mAh High Discharge Li-Po batteries (as shown in Fig. 2). Besides, the RP7972A Regenerative Power System from Keysight Technologies was employed to analyze and evaluate the power dynamics of the robot (Fig. 3). The voltage source's response, which delineates the relationship between the open Circuit Voltage (OCV) and the State of Charge (SoC), is ascertained through a series of pulsed charge and discharge experiments [5], [6]. The battery discharge profile was generated using a systematic methodology, capturing essential metrics such as SoC, OCV, and Internal Resistance (IR). The power consumption analysis encompassed powering on various components and sections of the robot and recording the behavior during teleoperation in different environments. By following these methodologies, valuable insights into power consumption patterns and the influence of environmental conditions on the robot's components and drive train were obtained.

A. PiBot: The service robot

Tecnológico de Monterrey's PiBot is a versatile autonomous service robot and research platform developed in 2019 [4]. Originally designed for medical assistance and last-mile delivery applications, PiBot's autonomy duration has remained uncertain due to the lack of a comprehensive power consumption and battery study. PiBot runs on Ubuntu 18.04 and utilizes ROS Melodic as the underlying framework for implementing its various algorithms and functionalities as a service robot.

PiBot relies on two Turnigy 14.8 V 4 cell 10,000 mAh High Discharge Li-Po batteries to meet its power requirements. The first LiPo battery is dedicated to supplying power to essential components such as the Arduino Mega, the Nvidia Jetson TX2, a ViewSonic touchscreen, an ethernet switch, a 4G router, four Thundercomm AI Kits, power electronics including voltage regulators and relays, and a USB HUB (externally powered, not by USB) that further provides power to other peripherals such as the RPLiDAR and two Intel Realsense D435i cameras. The power distribution of this first battery and PiBot's components is displayed in Fig. 2. It is important to note that any additional power consumption resulting from the various algorithms employed, including ROS nodes establishing communication with each sensor, publishing sensor readings, the navigation algorithm, or teleoperation, will affect the power consumption of this battery, as the majority of these algorithms run on the Nvidia Jetson TX2.

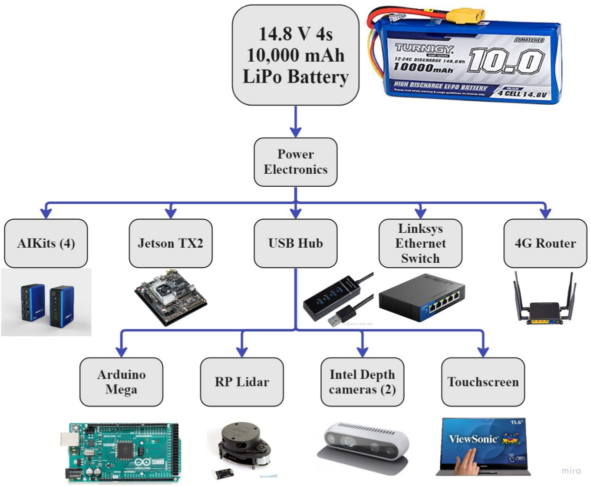

Fig. 2. The power distribution scheme of PiBot is illustrated, showing the interconnected components powered by the first Turnigy 14.8 V 4 cell 10,000 mAh Li-Po battery.

The second LiPo battery in PiBot serves as the dedicated power source for the drive train, which includes two dual RoboClaw motor drivers and four IG42 permanent magnet DC motors, each with a nominal voltage of 12 V and a maximum rotational speed of 200 RPM. These motors are responsible for actuating the mecanum wheels of PiBot as depicted in Fig. 1.

B. RP7972A Regenerative Power System: Power Analysis Tool

The power system selected for the power consumption study of the autonomous service robot was the RP7972A Regenerative Power System from Keysight Technologies, utilized in the ElectroMobility Laboratory at Tecnológico de Monterrey, a National Research Laboratory on Electromobility and autonomous vehicles. This power supply offered a robust platform with comprehensive features and capabilities,

Fig. 3. The RP7972A Regenerative Power System provided by the ElectroMobility Laboratory at Tecnológico de Monterrey, a National Research Laboratory on ElectroMobility and autonomous vehicles.

allowing for a thorough analysis and evaluation of the power dynamics of the robot.

One notable advantage of the RP7972A power system was its capability to emulate high-voltage, high-power batteries. This feature enabled the replication of the power source behavior used by the service robot with great accuracy during the experimental trials. By accurately emulating battery characteristics, such as programmable resistance, realistic power consumption patterns were mimicked, providing valuable insights into the robot's energy efficiency.

The power system's versatility was demonstrated through various modes utilized in this study. Following the detailed analysis of the battery's discharge profile, the RP7972A system facilitated battery simulation. By leveraging its emulation capabilities, the RP7972A system allows the behavior replication of the service robot's power source, accurately mimicking the power consumption patterns observed in real-world scenarios. This allowed for a comprehensive evaluation of the robot's energy efficiency and optimization of its power dynamics. In this specific test scenario, a controlled environment is employed to ensure that environmental factors such as temperature, humidity, and vibrations are deliberately excluded from consideration.

C. Methodology for Generating Battery Discharge Profile

To achieve the battery's discharge profile required for simulating the service robot's power consumption behavior, a systematic methodology was followed. The goal was to accurately capture the SoC, OCV, and IR of the battery. These metrics are recorded by the RP7972A Regenerative Power System for emulation of battery behavior. This subsection details an overview of the experimental procedure used to generate the battery's discharge profile:

1) Battery Preparation:
    - The Turnigy 14.8 V 4 cell 10,000 mAh High Discharge Li-Po battery, a rechargeable battery, was selected as the power source for the experiments.
    - The battery was fully charged before the discharge profile generation to ensure a consistent starting point. The charging process resulted in an open circuit voltage of 16.727 volts, indicating a fully charged state.
    - During the battery preparation process, it is essential to prioritize safety. All necessary safety precautions were taken during battery handling and experimentation to mitigate any potential risks.
2) Experimental Setup:
    - The RP7972A Regenerative Power System was employed as the power supply system for the battery discharge profile generation.
    - The system's discharge mode was selected and configured with key parameters to achieve the desired discharge characteristics. This included setting a constant current discharge type of 10 Amps, a voltage limit of 31.781 V, a capacity rating of 10 Ah, a rest time of 1 s, and a cut-off condition based on both voltage and current thresholds.
3) Discharge Profile Generation:
    - The battery discharge process was initiated, and data was collected at regular intervals (0.62 s) to capture the battery's behavior.
    - A predefined number of steps (200) were employed to ensure an accurate representation of the discharge profile.
    - The RP7972A system recorded and logged the metrics such as the elapsed time, voltage, and current measurements during the entire discharge process.
4) Data Analysis:
    - The collected data was analyzed to determine the SoC, OCV, and IR of the battery at various points during the discharge.

Through the successful implementation of this methodology, we generated the battery's discharge profile, which serves as a crucial input for simulating the power consumption behavior of the service robot. The captured profile, including metrics such as SoC, OCV, and IR, enables accurate energy efficiency analysis and optimization. This comprehensive profile will be utilized in our power consumption study of the service robot.

D. Power Consumption Analysis of Motors and Electronics

The power consumption analysis was conducted to evaluate the energy usage and behavior of the autonomous service robot under different operational scenarios. The methodology involved recording the power consumption behavior while powering on various components/sections of the robot and during teleoperation in different environments.

1) Powering On Procedure:
    - The system was operated in the discharge mode using the previously generated battery discharge profile.
    - Sequentially, the following components/sections were powered on:

  - Switching on the switches establishing the flow of electricity between each battery and the components they feed, including power electronics such as voltage regulators and relays.
  - Powering on the externally powered USB HUB where multiple components are connected.
  - Activating the Nvidia Jetson TX2, which also powers the 15-inch touchscreen.
  - Powering on the Thundercomm AI Kit systems, one by one, which are energized when the switches are switched but not fully powered on until this step. Each Thundercomm AI Kit system contributes to the overall functionality of the service robot, providing additional computational power and sensor capabilities.
  - Launching all sensor nodes algorithms on the Nvidia Jetson computer, establishing communication between the computer and various sensors, such as the RP LiDAR, the D435i depth camera, or the Arduino Mega for commanding the dual RoboClaw drivers.
- The powering on procedure was performed three times for the electronics load to ensure reliable data collection. The drive train power consumption during the power-on procedure was not measured as these actions do not affect drive train components consumption.

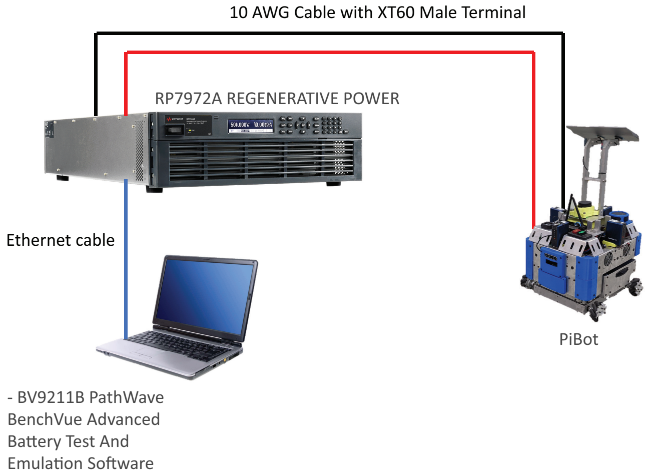

Fig. 4. Connection diagram to run the Emulation Test using Keysight's PathWave BenchVue Advanced Battery Test And Emulation Software

2) Teleoperation and Navigating in Different Environments: The autonomous service robot underwent teleoperated navigation in distinct environments with varying conditions to observe the influence on power consumption behavior in drive train components. In each experimental setup, variations in distance, surfaces, and slopes were intentionally introduced to study energy utilization patterns in realistic environments where the mobile robot is likely to operate offering variability rather than repeatability. In all scenarios, the robot was configured to navigate at a consistent speed of 0.1 m/s.
   - *Experiment 1*: Low Grip, Flat Indoor Environment. Initially, the robot was teleoperated on a ceramic floor offering a low grip. In each lap of this single run, the robot traversed 2 meters forward, executed a 180-degree rotation, advanced another 2 meters forward, and then performed another 180-degree rotation. This procedure was replicated three times consecutively in the same run, the laps being compared to ensure repeatability.
   - *Experiment 2*: High Grip, Flat Indoor Environment. This experiment involved navigating on a flat, high-grip surface, simulated using 36-grade sandpaper glued on a wood surface. During each run, the robot was teleoperated to advance 1.20 meters forward, pause for a second, and then retreat 1.20 meters backward. This trial was conducted thrice, with comparisons between runs conducted to ensure repeatability.
   - *Experiment 3*: High Grip, Inclined Environment. The final teleoperated experiment was conducted on a high-grip surface, again using 36-grade sandpaper, but this time on a 27-degree incline. In each run, the robot advanced 1.20 m uphill, paused for a second, and then navigated 1.20 m downhill, pausing once more before repeating. This set of maneuvers was performed twice in each run, with three separate runs conducted overall.

In all the procedures and experiments, power consumption patterns were meticulously recorded during execution. The goal was to discern the average power consumption across diverse environmental conditions, analyzing the impact of surface type, inclination, components, and maneuver patterns on the drive train and electronics power consumption behavior.

To perform this methodology, the Emulation Test setup is prepared as shown in Figure 5; where the positive and negative terminals from the RP7972A power system are connected to the PiBots's energy source terminals and the RP7972A system is also connected to a computer with PathWave BenchVue Advanced Battery Test And Emulation Software through an Ethernet cable. The physical depiction of the schematic diagram presented in Figure 4 is illustrated in Figure 5.

By following this methodology, it is possible to capture and analyze the power consumption behavior of the autonomous service robot under various operational scenarios. The recorded data provides insights into the energy usage patterns and the influence of different environmental conditions on the power consumption of the robot's components and drive train.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The analysis of power consumption is carried out to assess the energy utilization and performance of the autonomous service robot across various operational scenarios based on the generated battery's profile.

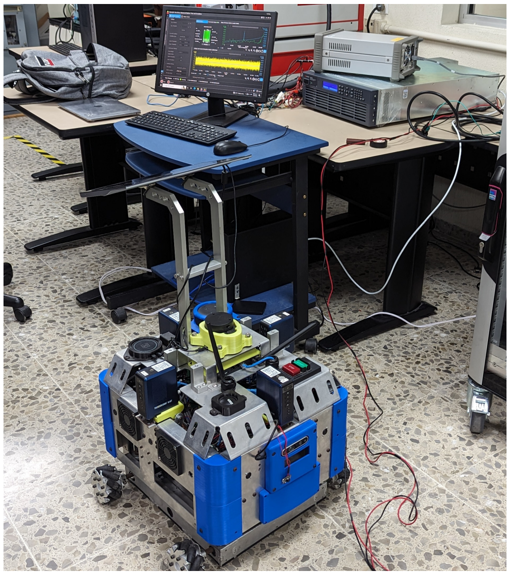

Fig. 5. Physical representation of connections used for the Emulation Test

From the generated discharging profile of the battery shown in Figure 6 a notable initial internal resistance of 0.23 Ohms can be observed, which experienced a marginal decrement to approximately 0.21 Ohms as the State of Charge approached 95%. An additional decline in internal resistance was observed within the range of 0.17 to 0.19 Ohms, persisting throughout the remainder of the experiment. This behavior can be attributed to the battery's increasing efficiency with increased SOC. This suggests an inverse relationship between the SOC and the system's internal resistance.

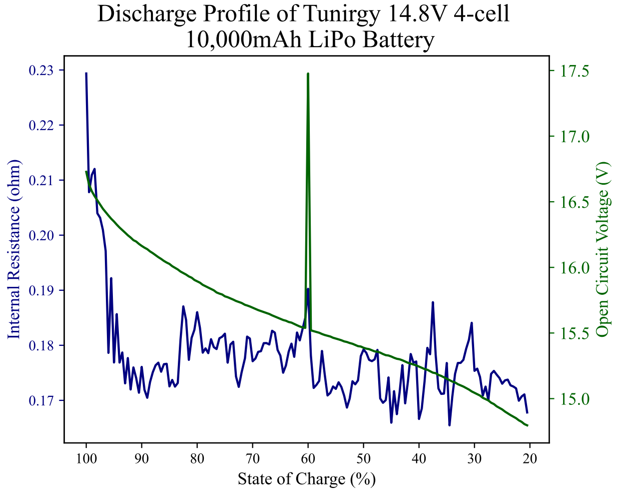

Fig. 6. Discharging Profile of Turnigy 14.8V 4-cell 10,000mAh LiPo Battery: The plot shows the relationship between the State of Charge (%), internal resistance (ohm) as well as open circuit voltage (Voc).

In terms of voltage characteristics, the system started with 16.727 V, subsequently experiencing a steady decrement of around 0.25 V for each 10% drop in SOC, indicative of the common battery discharge characteristic. Abnormal behavior was observed in the discharge profile, with the voltage momentarily surging to 17.5 V at approximately 60% SOC behavior. This unusual behavior is attributed to the RP7972A Regenerative Power System. This type of spike has been reported even by the manufacturer of the regenerative power system in previous battery discharge profiles, and it is due to an internal configuration. It must be noted that this atypical action has no effect when simulating the battery as SOC never dropped below 90%.

During the Powering On Procedure, the power consumption exhibits an incremental pattern by which the activation sequence of electrical components prioritizes those with lower energetic impact, progressively followed by components with higher impact. Based on the examination of the plots presented in Figure 7, it is deduced that the actions of "Turn switches", "Power USB HUB", and "Launch sensor nodes" exhibit relatively lower energetic impact, as indicated by minimal voltage drop and current increase. Conversely, the actions of "Power on Jetson" and each of the four instances of "Power on AI Kit" demonstrate the highest energetic impact, characterized by significant voltage drop and current increase.

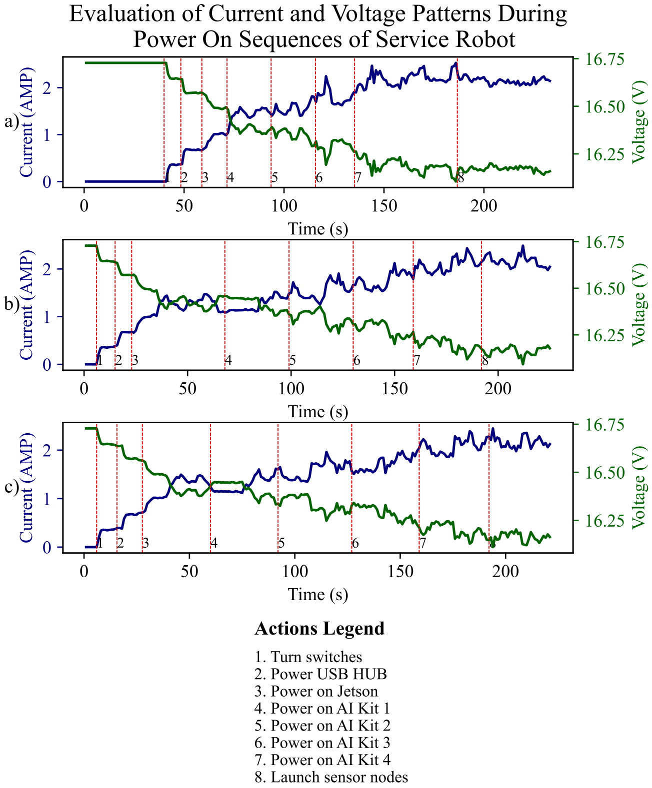

Fig. 7. Current and voltage changes due to distinct power-on events of the autonomous robot, divided by individual power-on sequences into subplots a, b, and c. Notable actions such as activating the USB HUB or powering on the Nvidia Jetson are indicated by red dashed lines.

As determined from the plots in Figure 7, the electrical system is found to consume approximately 2.5 amperes (A) of current. Considering the battery capacity of 10 ampere-hours (Ah), it is reasonable to anticipate an estimated autonomy duration of approximately 3.5 hours for the electrical system, considering that it should not be drained completely.

Throughout the Teleoperation and Navigating Procedure, the power consumption displays a consistent energy utilization pattern that corresponds to the specific situation and surface conditions encountered during the service robot's navigation. During the navigation across a level surface, the autonomous service robot executed three consecutive laps, each consisting of a forward advancement of 2 meters followed by a 180-degree rotation. Notably, completing two such cycles constituted one full lap. The current consumption throughout this patrol, as depicted in Figure 8, demonstrated a consistent range of approximately 3 to 3.5 A.

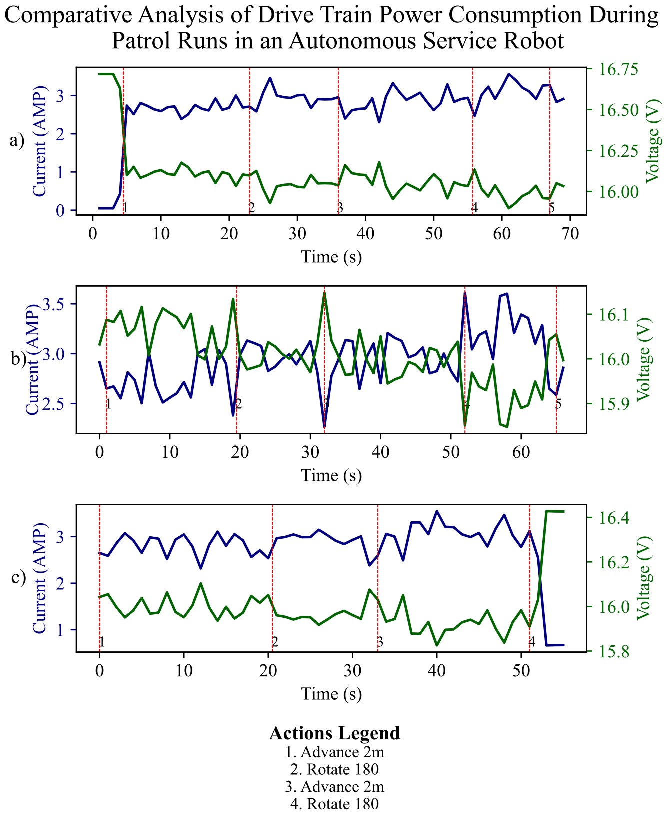

Fig. 8. Current and voltage changes during patrol runs of the autonomous robot in *experiment 1*, divided by individual run sequences into subplots a, b, and c. Notable actions such as advancing or rotation sequences are indicated by red dashed lines.

In its teleoperation on a high-grip surface displayed in Figure 9, the robot displayed a stable power consumption pattern. On initiation, both voltage and current readings settled to a stable baseline, indicating the equilibrium of the robot's power system at rest. Upon movement initiation, there was a rise in current to around 3 A, accompanied by a voltage drop to about 16 V. This can be interpreted as the robot's system adjusting its power distribution to accommodate the increased demand for forward navigation.

Upon reaching a distance limit and stopping, the current dipped slightly above 1 A, while the voltage rose, stabilizing near 16.25 V due to the reduced energy demand as the robot ceased movement. This distinct behavior was consistently observed across all three runs, providing vital insights into the robot's power dynamics during active and inactive states.

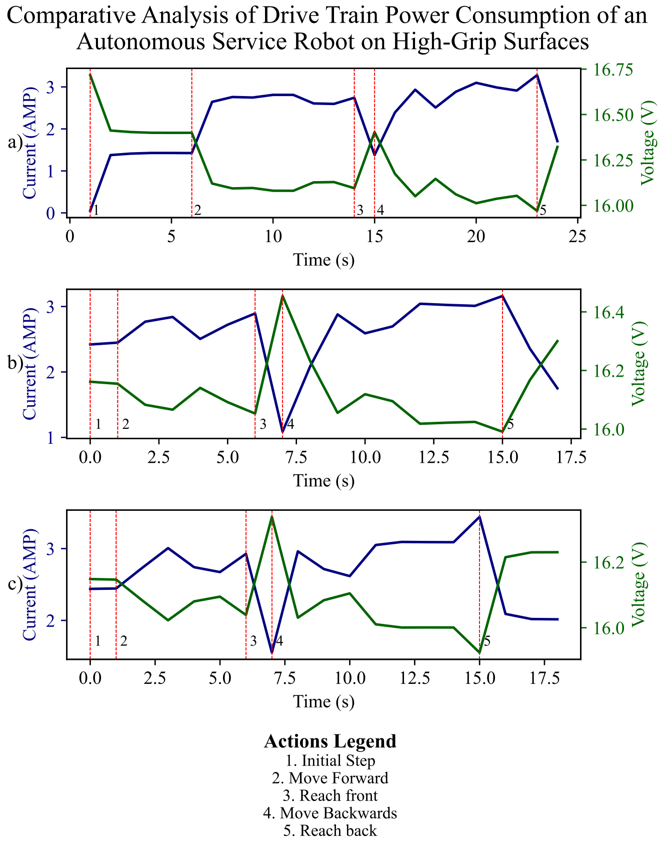

Fig. 9. Current and voltage changes during *experiment 2* of the autonomous robot, divided by individual run sequences into subplots a, b, and c. Notable actions such as moving or reaching positions are indicated by red dashed lines.

In comparison, during the navigation across a 27-degree inclined surface, the autonomous service robot followed a sequence where first an initial step was made to capture the consumption of the robot while holding static on the ramp, then three consecutive laps of moving forward, reaching the top, moving backward, and reaching the bottom followed. This process was executed three more times. Based on the analysis of the data presented in Figure 10, it can be inferred that when the autonomous service robot is stationary on an inclined surface (up to a maximum angle of 27 degrees), the current consumption reaches approximately 4 A. During ascent, the current consumption ranges between 7 to 9 A, whereas during descent, it ranges from 2 to 3 A.

In Figure 10c, a transient peak in current is observed between seconds 24 and 26. This momentary surge can be attributed to the necessity of slightly adjusting the robot's orientation to keep it within the high-grip area. Given the inclination of the surface, this slight rotation required two of the motors to work against gravity (uphill) while the other two operated with gravity (downhill), thereby drawing an increased amount of current momentarily.

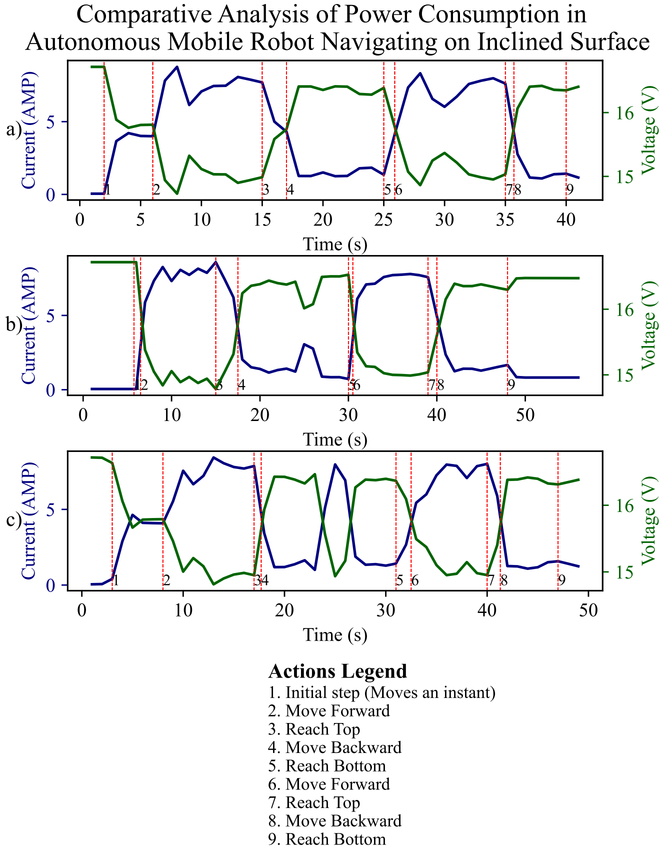

Fig. 10. Current and voltage changes during *experiment 3* of the autonomous robot in a high grip and inclined (27-degree) environment, divided by individual run sequences into subplots a, b, and c. Notable actions such as advancing or rotation sequences are indicated by red dashed lines.

IV. CONCLUSIONS

The analysis of power consumption provided valuable insights into the energy utilization and performance of the autonomous service robot across various operational scenarios. Based on the generated discharging profile of the battery a decline in internal resistance was observed after crossing the 95% State of Charge (SOC), from which can be concluded that an increased battery efficiency with higher SOC levels is expected. Additionally, the voltage characteristics displayed a consistent decrement of approximately 0.25 V per 10% drop in SOC, with a momentary voltage surge to 17.5 V observed at around 60% SOC, warranting further investigation into the underlying causes.

Considering the observed current consumption during the Powering On Procedure of approximately 2.5 amperes, and an average of 4 amperes during the Teleoperation and Navigating Procedure. The estimated autonomy duration of the electrical system and drive train with an independent 10 Ah battery capacity is approximately 3.5 hours and 2 hours of continuous movement autonomy, ensuring the battery is not completely drained. However, it is essential to acknowledge that, as of the current investigation, we have not yet conducted tests to determine the actual autonomy of the robot. This aspect will be addressed in our future research efforts as part of our ongoing work.

The analysis highlights that the Jetson and AI KITs are the elements that contribute the most to energy drainage, while navigating upwards on an inclined surface and maintaining static on it result in the highest energy consumption. These observations underscore the importance of considering the energy consumption of these specific electrical equipment and actions in future investigations and during the selection and design of batteries for autonomous service robots. Such considerations are crucial for optimizing the energy efficiency and overall performance of these robots.

These findings provide valuable insights into the energy utilization and behavior of the autonomous service robot, contributing to the optimization and improvement of its performance in various operational scenarios.

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