Mining Energy-Related Practices in Robotics Software

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Abstract—Robots are becoming more and more commonplace in many industry settings. This successful adoption can be partly attributed to (1) their increasingly affordable cost and (2) the possibility of developing intelligent, software-driven robots. Unfortunately, robotics software consumes significant amounts of energy. Moreover, robots are often battery-driven, meaning that even a small energy improvement can help reduce its energy footprint and increase its autonomy and user experience.

In this paper, we study the Robot Operating System (ROS) ecosystem, the de-facto standard for developing and prototyping robotics software. We analyze 527 energy-related data points (including commits, pull-requests and issues on ROS-related repositories, ROS-related questions on StackOverflow, ROS Discourse, ROS Answers and the official ROS Wiki).

Our results include a quantification of the interest of roboticists on software energy efficiency, 10 recurrent causes and 14 solutions of energy-related issues, and their implied trade-offs with respect to other quality attributes. Those contributions support roboticists and researchers towards having energy-efficient software in future robotics projects.

I. INTRODUCTION

The intensive use of robots is becoming a successful, commonplace story in several industrial sectors like manufacturing, logistics, delivery, transportation, healthcare [1]. With large players such as ABB, Siemens, and Mitsubishi, it is estimated that the revenue generated from the industrial robotics market worldwide will be 18.25 billion USD in 2025 [2]. One of the most important reasons for the success of robotics is the possibility of equipping robots with intelligence [20]. With intelligent robots, software comes into the picture, becoming the core aspect in robotics development [31]. [4].

One of the key technological enablers for robotics software development is the Robot Operating System (ROS), a communication framework for robotics software modules [45]. ROS is the de-facto standard for developing and prototyping robotics software. It supports 162 different types of robots and has a vibrant open-source ecosystem, including 6,096 publicly-available software packages, 9,148 ROS Wiki users, and 36,901 ROS Answers users [4], [20].

Robotics software can consume substantial amounts of energy. For example, the automotive industry alone in the U.S. spends 2.4 billion USD on electric energy annually [11] and industrial robots in the automotive industry consume on average 8% of the total electrical energy of assembly lines [34].

In this context, even a slight energy improvement can lead to great benefits in terms of environmental impact, mission completion time (e.g., fewer pauses for recharging batteries), and safety (e.g., a flying drone crashing due to poorly-managed energy consumption). Even though there is a relatively rich body of literature on energy efficiency for robotics [50], it is still unclear how practitioners are dealing with energy-related aspects in projects developed in real contexts.

The goal of this paper is to characterize the recurrent practices of roboticists in the field, specifically: (i) to quantify the interest of practitioners on energy aspects of robotics software and (ii) to obtain a deeper understanding of the main causes, solutions, and trade-offs of energy-related issues in robotics software.

In this work, we apply software repository mining techniques targeting (i) developers’ discussions on StackOverflow and official technical forums used by ROS developers (e.g., ROS Answers) and (ii) the source code, documentation, commit messages, issues, and pull requests in 335 Git repositories containing real open-source ROS systems [31]. Out of 339,563 potentially-relevant data points [4], we systematically curate a final set of 527 data points where developers discuss, mention, or consider energy in the context of their ROS systems. We then employ quantitative and qualitative data analysis techniques to extract and synthesize roboticists’ practices with respect to energy; specifically: how much roboticists consider energy-related issues in their projects, 10 recurrent causes and 14 solutions of energy-related issues, and their implied trade-offs with respect to other quality attributes like reliability and performance. The main contributions of this study are:

- a quantification of the interest of practitioners in the energy aspects of robotics software;
- a taxonomy of the main causes and solutions of energy-related issues faced by roboticists;
- the identification of the quality attributes considered by roboticists when facing energy-related issues;
- a manually curated and validated dataset of 527 energy-related data points in the context of robotics software;
- the complete replication package of the study.

†We use the term data point as the superclass of any type of mined item, such as a commit message, a GitHub issue, or a discussion on StackOverflow.
The target audience of this study includes both roboticists and researchers in green software engineering. Roboticists can benefit from the taxonomy of energy-related issues by using the extracted causes as a checklist of the various aspects of their system to be taken under consideration and by using the extracted solutions as a catalog of concrete solutions in case their system suffers from an energy-related issue. Researchers get an objective characterization of the state of the practice about energy-related aspects in robotics software. Moreover, researchers can use the extracted causes and solutions as a foundation for defining new approaches to automatically improve the energy efficiency of robotics software.

II. BACKGROUND

The ROS Community - The ROS community is rapidly growing and especially active; when a developer encounters a problem, finding solutions and getting help becomes easier – not only from developers of the ROS platform but also from other enthusiasts and professionals. The primary communication channels and resources used in the ROS community are:

i) Stack Overflow and ROS Answers: Q&A websites which are used as one of the main communication channels for solving problems;

ii) ROS Discourse: a discussion forum mainly used for discussing more complex topics and announcing new projects and updates concerning the ROS community;

iii) GitHub: a repository hosting service where the majority of ROS packages are hosted at and which provides a Pull Request (PR) and Issue section of the package repository where questions and bugs concerning the ROS package can be discussed, and;

iv) ROS Wiki: a collection of various ROS tutorials, packages, and libraries.

Every day members part of the ROS community are heavily involved in the open-source development of publicly available ROS packages. As of July 2020, there are a total of 16,044 packages published on the official ROS website. According to ROS Community Metrics Report for July 2020, there are roughly 142,000, 199,000, and 21,400 registered users respectively for ROS Answers, ROS Wiki, and ROS Discourse.

ROS-based Systems - A ROS-based system is composed of Nodes which are OS processes that perform computations. A registered Node can interact with other Nodes using a publish/subscribe model based on Topics (publish and subscribe to messages), or using a request/response model based on Services or Actions (request and receive responses). A Service is a communication model that operates on the principle of synchronous bidirectional communication between a Service Client that requests data and a Service Server that responds to requests. Service calls are blocking so they are typically used for remote procedure calls that terminate quickly (e.g., simple calculations, querying the state of a Node). The Action communication model is used when the requested task takes a long time to complete and feedback from the process is needed (e.g., moving the robot).

We designed this study by following known empirical guidelines. A full replication package is publicly available for independent verification and replication.

III. STUDY DESIGN

A. Goal and Research Questions

The goal of this study is to analyze the ROS software ecosystem for the purpose of quantifying and characterizing the main causes, solutions, and eventual trade-offs of roboticists’ issues with respect to their energy efficiency from the point of view of roboticists and researchers in the context of open-source ROS-based systems. The goal drives the design of the full study and leads us to the following research questions.

RQ1 – To what extent do roboticists consider energy consumption in the context of robotics software? By answering this research question we aim at quantifying the interest in energy consumption of roboticists (i) over time and (ii) across different types of robotic systems and capabilities.

RQ2 – What are the main causes of energy-related issues reported by roboticists? This research question targets energy-related issues. In this study, energy-related issues are defined as errors, bugs, faults, or failures affecting the energy consumption of a robotic system, either purposely (e.g., streaming a high-definition video to the Cloud) or accidentally (e.g., a software bug leading to unnecessary CPU cycles).

RQ3 – What are the main solutions that roboticists apply or recommend for solving energy-related issues? This research question is the counterpart of RQ2. Specifically, RQ3 aims at identifying and characterizing the most prevalent solutions either applied or reported by roboticists for solving energy-related issues.

RQ4 – What are the quality attributes mentioned by roboticists when considering energy-related issues? As ROS-based systems are becoming more and more large and complex, it is critical that their software meets quality requirements such as maintainability, safety, and reliability.

B. Dataset Building

Figure 1 gives an overview of the process we followed for building the dataset for answering our RQs. We consider the following starting data sources: Open-source Git repositories, Stack Overflow, ROS Answers, ROS Discourse, and ROS Wiki. For the open-source repositories, we consider the GitHub, Bitbucket, and Gitlab social coding platforms. In this context, we reuse an already-existing dataset of 335 repositories containing real and active ROS-based projects. We locally clone each repository and extract all its source code comments and markdown files (Code Extraction in Figure 1). We also mine all issues/pull requests (including their discussions) and commit messages (Git Extraction in the figure). For Stack Overflow, ROS Answers, and ROS Discourse we crawl all questions, their answers, comments, and related (meta-)data. Since Stack Overflow is not specific to ROS, we target questions with the ROS tag. For ROS Wiki, we crawl all its pages and related (meta-)data. All extracted data points are persisted in a MongoDB database. Since MongoDB is
Finally, we query our MongoDB database by considering the list of energy-related search terms. After an initial inspection of the obtained search hits, we noticed that we were having several false positives. For instance, the term green leads to matches including forms like green LED, green button, that are clearly out of scope for this study. To mitigate this threat, two researchers randomly sampled a subset of the search results and collaboratively identified a set of combinations of terms that are out of scope, we call them taboo terms. Examples of taboo terms are coefficient, time consuming, and green icon. Then, we filter out all the search results matching with at least one taboo term. This results in 5,111 data points containing energy-related terms. The high discard-rate in this step is not surprising, but it is rather in accordance with existing research confirming that developers tend to have limited knowledge of energy efficiency.

### TABLE I: Studies used for extracting energy-related terms.

| Paper | Domain | Targeted Data |
|-------|--------|---------------|
| Li et al. [27] | Mobile | Issues |
| Swanthorn and Malavolta [50] | Robotics | Literature |
| Cruz and Abreu [16] | Mobile | Commits, Issues, PRs |
| Moghadam, Lago, and Ban [35] | Generic | Literature |
| Matalonga et al. [33] | Mobile | System Events |
| Chowdhury and Hindle [13] | Generic | Commit Messages |
| Bavota [9] | Generic | Commit Messages |
| Moura et al. [42] | Generic | Commits |
| Malik, Zhao and Godfrey [33] | Generic | Stack Overflow |
| Procaccianti, Lago and Bevini [44] | Cloud | Literature |
| Pinto, Castor and Liu [42] | Generic | Stack Overflow |
| Procaccianti, Bevini and Lago [43] | Cloud | Literature |
| Calero, Bertoa and Moraga [10] | Generic | Literature |
| Pathak, Hu and Zhang [28] | Mobile | Issues, Forum Posts |

### Phase 2 –

In this phase we manually analyze all the 5,111 data points for removing false positives. This phase is performed systematically and iteratively by three researchers. In a first iteration, we perform a stratified random sampling of 398 data points according to their type; specifically, we randomly sample 50 data points for each type of data point (i.e., 50 Git commits, 50 Stack Overflow discussions, and so on). Then, two researchers independently assess whether each sampled data point is a false positive. We verify the inter-rater agreement via the Cohen’s Kappa coefficient [47], which is 0.82, thus resulting in an almost perfect agreement. Then, we discuss and solve the occurred conflicts with the help of a third researcher acting as arbiter. Subsequently, we repeat the same process by considering another random sample of 50 data points for each type of data point; this time the Cohen’s Kappa coefficient increases to 0.84, making us confident about the objectivity of our manual classification. Based on the good inter-rater agreement obtained in the first two iterations, one researcher proceeds to classify the remaining data points, with the help of another researcher in case of doubts. This phase results in 527 energy-related data points.

### Phase 3 –

When performing a keyword-based search, it is fundamental to minimize the number of false negatives [9]. i.e., data points that do not contain any of energy-related terms in our list but are about energy. In this context, we are interested in the data which have not been selected in Phase 1.
e.g., in several previous studies on energy-efficient software, emerging patterns are used to answer RQ2 and RQ3. We chose knowledge is the set of applying thematic analysis – These research questions are answered by RQ2 and RQ3. Then, we apply simple summary statistics to answer RQ1.

C. Data Analysis

The selected energy-related data points are analyzed in three different ways in order to answer the research questions, where we follow the same strategy to answer RQ2 and RQ3. All the data analysis is detailed in the remainder of this section.

RQ1 – Firstly, we collect the creation date of each of the 527 data points in our dataset. Then, two researchers conduct iterative content analysis sessions with open coding [28] to extract information related to (i) the considered types of robots (e.g., ground rover, flying drones, industrial arms) and (ii) their provided capabilities (e.g., vision, navigation, manipulation). Then, we apply simple summary statistics to answer RQ1 quantitatively.

RQ2 and RQ3 – These research questions are answered by applying thematic analysis [21], [18], [51]. Thematic analysis is a qualitative research method for identifying emerging patterns from a body of knowledge. In our study, the body of knowledge is the set of 527 energy-related data points, and the emerging patterns are used to answer RQ2 and RQ3. We chose thematic analysis because (i) it has been successfully applied in several previous studies on energy-efficient software, e.g., [36], [16] and (ii) the information we extracted from each data point is strongly dependent on project- and system-specific characteristics and thematic analysis copes well with context-dependent data [51], [18]. By following the guidelines reported in [21], three researchers carried out the thematic analysis according to the following steps:

1) Familiarisation with the data – The three researchers carefully inspect all 527 data points to become familiar with the dataset. When a data point is about concepts/techniques which are not common or unclear, we study them using either related scientific literature or online documentation (usually via the official ROS Wiki).

2) Extracting initial codes – The goal of this step is to extract descriptive labels from segments of text from each data point. Examples of extracted labels are: “high modulation frequency”, “mpeg_server is power consuming”, “land when battery is low”. We extracted the initial codes in five main steps. In the first one, we randomly sampled 80 data points (10 for each type – see Table II) and three researchers code them in parallel; in the second step, the extracted codes are largely discussed in order to identify differences of perspectives and spot potential sources of subjectivity. No substantial differences were identified in the extracted codes. In the third step one researcher proceeds with extracting the codes of the remaining data points, with the help of the other two researchers in case of doubts. Once all the codes are extracted, in the fourth step we collaboratively and iteratively combine codes with the same meaning, resulting in a final set of 494 unique codes. Finally, in step 5 we group the extract codes according to the research questions they may answer, leading to 158 codes related to RQ2 and 307 codes related to RQ3 (with 24 codes belonging to both groups). Contextually, we discard 52 codes that are not related either to RQ2 or RQ3.

3) Searching for themes – The goal of this step is to combine the extracted codes into an initial set of themes. For each RQ, two researchers navigate through the extracted codes and organize them into meaningful subsets. Then, for each subset, a precise theme was formulated. We focused on making the phrasing of the themes (i) representative of its corresponding codes, (ii) not overlapping, and (iii) actionable to be readily usable by roboticists in the field. This activity resulted in a total of 28 themes for RQ2 (the causes of energy-related issues) and 41 themes for RQ3 (their solutions).

4) Reviewing themes – In this step we go back to the extracted codes once again in order to rearrange the codes and refine themes. Here, generic themes are split into more specific subcategories, others are renamed (when necessary), and codes are moved from one theme to another (when necessary). While reviewing the codes, we search for data that supports or refutes themes. In most cases, we only go back to the extracted codes. When the extracted codes are not descriptive enough, we go back to the initial data points. This activity resulted in a total of 24 themes, 10 themes for RQ2 and 14 themes for RQ3.

5) Defining and naming themes – In this step, two researchers finalize the name and produce a structured description of each of the 24 themes. The description of each theme is based on the data points in our dataset (e.g., a solution described in a GitHub pull request), the researcher’s experience, logical arguments, and the scientific literature. Finally, the phrasing (and semantics) of each theme undergo rigorous scrutiny of one additional researcher, leading to a further refinement of the emerged themes.

6) Producing the final report – In this phase, all authors of this study carefully scrutinize the emerged themes, contextualise them, and further refine their definitions.

RQ4 – For our last research question, we revisit all 527 data points that have been qualitatively analyzed to answer RQ2 and RQ3. In this second round of assessment, we revisit the data points focusing on quality attributes mentioned in the discussion/code change. We use the quality attributes defined in the ISO/IEC 25010 standard [5] as the initial set of codes, which encompasses eight main groups, namely: Functional Stability, Performance, Compatibility, Usability, Reliability, Security, Maintainability, and Portability. For each data point, we verify if there is any mention of these quality attributes. Ultimately, we conduct content analysis sessions on the data points mentioning at least one quality attribute and report the frequency in which each quality attribute is mentioned contextually to energy, together with a description of notable/representative examples.
IV. RESULTS

A. Consideration of energy-related issues (RQ1)

Energy-related discussions are rare in the analyzed artifacts. We discovered 527 (0.002%) energy-related data points out of our initial dataset of 339,563. The most common types of energy-related data points were ROS Answers discussions (30.93%), Git commit messages (26.19%), Git issues (22.01%), and Git pull requests (11.76%).

| Type of data point                  | All     | Energy-related | Pct.         |
|-------------------------------------|---------|----------------|--------------|
| ROS Answers discussions             | 43,672  | 163            | 30.93%       |
| Git commit messages                 | 218,385 | 138            | 26.19%       |
| Git issues                          | 23,214  | 116            | 22.01%       |
| Git pull requests                   | 30,096  | 62             | 11.76%       |
| Source code                         | 16,069  | 18             | 3.42%        |
| ROS Discourse discussions           | 2,604   | 17             | 3.22%        |
| ROS Wiki pages                      | 2,547   | 12             | 2.28%        |
| Stack Overflow discussions          | 1,880   | 1              | 0.19%        |
| **TOTAL**                           | 339,563 | 527            | 100%         |

Table II shows the distribution of energy-related data points among all considered types of data points. Most of these data points are associated to ground (36.8%), generic (24.5%), and aerial (12.5%) robots. Most of these energy-related data points are associated to robots with full (35.5%), base [25%], and infrastructural (10.1%) capabilities. The most common energy-related terms in our dataset were \*battery\* (45.73%), \*power\* (15.75%) and \*charg\* (12.58%). Figure 2 shows the energy-related data points overtime per robot type in the time span between 2008-2020. The years 2011 and 2012 showed considerable more energy-related discussions than the rest of the considered years. The figure also shows that ground robots were the most prevalent in these two popular years, albeit their popularity decreased significantly in the upcoming years.

**Fig. 2: Energy-related data points over time per robot type.**

B. Main causes of energy-related issues (RQ2)

Out of the 527 energy-related data points, we identified a total of 109 (20.68%) distinct ones referring to \*causes\* of energy-related issues. Then, we further analyzed those 109 data points and extracted 10 recurrent themes. For the sake of space, in the following, we describe the 5 most frequent themes, together with concrete examples and quotations helpful for understanding the context in which energy-related issues may arise in ROS-based systems.

**Battery physical properties** (29) – Robots can be equipped with batteries with widely different operating principles, voltage, and form factors, ranging from standard laptop batteries to sodium-ion batteries, micro-scale lithium-ion batteries, etc. As emerged in our analysis, not taking into account those properties can lead to energy-related issues such as unexpected drops in the voltage provided by the batteries, which can lead to a sudden halt of the system, or fast energy draining. For example, in DP221 we can get a clear understanding about the types of battery-related issues a roboticist might have to deal with: “Kinect can actually handle a small voltage swing pretty well. I had no problems with 11 to 13.5V although I would advise against it. Using a typical 7812 or LM1084-12 is the best option. Also, an ATX output provides a stable 12V (sometimes they do need a minimal load). The Kinect PSU is rated for 1 or 1.5A, but using the Kinect with camera + pointcloud only, I never got it above 500mA. However, the current peaks can bring the robot down”.

Moreover, the physical properties of batteries degrade over time, even when they are not used. For example, in DP410 a roboticist mentions that “if you charge the [Kobuki] batteries and then unplug them, they should survive 6 months to a year. Open the bottom of the Kobuki and unplug the battery pack. And remove the battery from the laptop, like it was shipped.”. These specific types of energy-related causes are especially cumbersome since they might lead to transient bugs, which are difficult to reproduce while testing the system.

**Bugs and technical issues in the source code** (24) – The majority of data points in this family are about bugs in the source code, which leads to energy-related issues. For example, in DP376, a roboticist refers to a bug in the Onboard SDK which has been fixed in the 3.9 version with the following release note: “Battery Information ROS Topic: Fix bug and implement the battery information of ROS topic” [3].

Energy bugs can escalate into failures impacting the whole robotic mission. In DP218 the port used by the controller of a robot was not correctly specified in the ROS parameter server, leading to the situation where “the battery [of a Pioneer 3-DX robot] is 0% even though the robot is fully charged. [The developer is] not able to enable or disable the motors.”. Similar failures can be caused by other types of bugs, such as erroneous management of physical units; e.g., in DP347, battery charge was provided in mAh by the driver, but its corresponding ROS node was publishing it as Ah. The problem of physical units inconsistencies is recognized in the literature and there are approaches for their automatic detection, e.g., via static analysis and probabilistic inference [26].

Other causes of code-related energy issues include technical debt (DP320), and the difficulty of developing embedded software for novice developers, which might involve cross-compilation and manual deployment of binary code (DP6).
ROS nodes configuration (17) – From an architectural perspective, ROS-based systems are composed of independently-deployed nodes mostly communicating asynchronously via publish/subscribe messages. If on one side the ROS architectural style supports developers in terms of maintenance and portability [31], on the other side in our dataset we observe that configuration errors of ROS nodes can lead to energy-related issues. In several data points, the root cause of those configuration errors is located in the launch file of the system, where roboticists either did not correctly remap topics or specified erroneous arguments when declaring ROS nodes. These types of problems can lead to severe consequences. For example, in DP346, the ROS topic for the battery voltage is not visible at all within the system, potentially leading to ROS nodes subscribing to topics that will never produce any data. Moreover, such problems might lead to missing system-wide diagnostics information, thus potentially leading to safety or reliability issues. For example, in DP388 “The diagnostics interface was written for/around the voltage reporting abilities of the V2 [of a Segway-based robot]. The V4 segbots have much more rich battery information (State of Charge for both the propulsion and auxiliary battery) which is not tracked by Hardware Diagnostics. Additionally, sensors such as the Velodyne VLP-16, sensors specific to the V4, are not tracked by Diagnostics.” In other cases, the configuration of the system is done without taking into consideration the execution environment of the system. For example, in DP316, the ROS node in charge of providing information about the battery charge of the laptop continuously publishes warning messages to other nodes, even if the battery is not present (i.e., the laptop is powered directly via its power adapter): this misconfiguration results in a high number of irrelevant messages published during the whole duration of the robotic mission, thus leading to a severe communication overhead.

Robot navigation (11) – As shown in Section IV-A mobile robots like rovers and drones are particularly discussed in the ROS ecosystem. As confirmed by the literature [50], one of the main energy consumers in mobile robots is robot navigation (e.g., robot acceleration, deceleration, turns). This phenomenon can be traced back to the fact that mobile robots heavily interact with hardware components that are particularly heavy on the battery, such as servos, motors, etc. For example, in DP384 the well-known ros-planning/navigation2 ROS package is extended with a new feature for configuring the maximum speed of the robot at runtime is proposed as a way to reduce the energy consumption of the robot.

Execution environment (e.g., board, OS, SDK) (11) – The execution environment of the ROS nodes is also influencing the energy consumption of the controlled robot. This phenomenon can happen at different levels of abstraction, ranging from the board where the ROS nodes are running (e.g., DP6), to the OS (e.g., DP198) or the used Software Development Kit – SDK (e.g., DP376). As an example, the discussion in DP48 includes a suggestion about recommended Single-board Computers (SBC) for ROS development saying that roboticists “need an SBC with at least a 1.0 Ghz modern CPU + 2GB of RAM. If power consumption is not a concern, [the roboticist] would recommend Intel Core CPUs over Atoms.”. This example highlights the fact that the choice of used processor impacts the energy consumption of the robot.

Other notable themes (40) – Other notable causes of energy-related issues include: streaming images/videos (10 occurrences), interaction with sensors and actuators (9 occurrences), providing feedback to a GUI (8 occurrences), raw computation (7 occurrences), and networking (3 occurrences). Overall, the emerged themes are expected and most of them have been already identified as sources of energy-related issues in the literature, both for robotics software [50] and other domains like mobile apps [41, 42, 24]. This result of our study confirms that roboticists are facing in practice similar causes as in other application domains.

C. Main solutions for energy-related issues (RQ3)

From the 494 distinct codes emerged in this study, we classify 303 as a solution. Those codes cover 380 (72.11%) data points out of the 527 we select as energy-related, which results in 14 distinct solution themes. Due to space limitations, in this study, we describe the 6 most recurring solutions (they describe together 85.54% of the solution data points).

Energy monitoring and tracking (166) – Most of the solutions that we found are discussions or implementations of monitoring and tracking of energy parameters. This phenomenon can be related to the fact that robots, likewise other battery-based devices, need to be aware of their battery conditions, such as their charge and remaining operational time. Autonomous robots also self-adapt based on battery information, where their behavior is updated in order to save energy when the battery level is low, or even favor processing when the battery level is not a constraint [50]. Therefore, monitoring and tracking energy parameters is a key element when dealing with energy efficiency.

Data point DP111 gives a concrete example of the importance of energy monitoring in a robotics system: “the robot monitors its battery level on a topic called /battery_level using a SMACH MonitorState which is part of the state machine SM_MONITOR_BATTERY. [...] If the battery level falls below a threshold (SM_MONITOR_BATTERY returns "invalid"), SM_MONITOR_BATTERY transitions to another state called RECHARGE that moves the robot to the docking station (NAV_DOCKING_STATION) and recharges the robot.” We see that the robot relies on the energy information delivered in a ROS topic by a dedicated battery monitor. In this case, without the battery information, the robot cannot go back to its docking station to self-recharge, thus potentially affecting the success of the robotic mission.

Voltage and current are the most commonly monitored metrics. In addition, the internal battery temperature is also considered in 4 data points. Battery temperature is supported by the ROS Smart Battery System (SBS); data point DP2 shares the ROS SBS specifications as an attachment that
considers the internal battery temperature as an important parameter for a safety check. For instance, in DP2 a temperature alarm is “set when the Smart Battery detects that its internal temperature is greater than a preset allowable limit. When this bit is set, charging should be stopped as soon as possible.” This can avoid battery damage and keep its physical characteristics fit, which may increase battery lifetime, and as consequence, make robots more energy-efficient.

Adaptations in robot behavior (101) – Several solutions rely on the robot adapting itself in order to respond to (excessive) energy consumption. We find three (non mutually-exclusive) adaptations that are common among our data points:

- **Abort mission:** the robot stops what it is doing due to energy restrictions. As an example, data point DP84 is about a flying drone where the energy level of the drone is the main factor for deciding whether the drone should fly or not. In this specific case, if the battery level is below a given threshold, the drone should try to land (both while taking off or when traveling towards a certain location).

- **Shutdown:** the robot shuts down itself and the other parts that hold it. In data point DP103, a roboticist asks others how to shut down the whole system when the battery level reaches a certain threshold. Data point DP176 illustrates another case, where another roboticist goes further and asks how to make this decision based on ROS messages. For DP103, others suggest creating a service with superuser rights that can be invoked to turn the whole system off.

- **Limit robot capabilities:** once the energy level is low, the robot decreases the resources allocated to some capabilities or even disables those that are not vital for the completion of the mission. For example, DP50 suggests to trade-off image resolution and frame rate to reduce energy consumption; in normal operations, the robot publishes high-quality images, but it decreases their quality when the battery is below a certain threshold. Data point DP159 illustrates a situation where the Kinect device is completely disabled in order to save energy. This can be used either when a sensor has not been used for a while or when the robot can switch to another less energy-consuming sensor, in case precision can be traded off. Both solutions present themselves as pertinent strategies when the robot depends on or supports human intervention. In those cases, the robot sends a notification to the roboticist for informing them that (i) it is running out of battery and (ii) it is working with limited features. This gives the roboticist some time to react; and then, replace batteries, or recharge them.

- **Other adaptations:** Our study also reveals other less frequent adaptations related to energy efficiency:
  - Go back home (e.g., DP423): the robot returns to its dock station or the starting point of the mission;
  - Charge during the mission (e.g., DP18): the robot keeps performing the mission, while its batteries are recharged;
  - Hibernate (e.g., DP5): the robot enters a hibernation state until its batteries are recharged.

User interfaces for assisting operators (56) – ROS systems usually provide a user interface (UI) for making the mission operator aware of the energy status of the robot. Despite those are summary solutions, they are a key element for energy-efficient robots since they provide periodic updates about the energy conditions of the robot to roboticists and warn/alert them in case of critical energy issues. In our study, we identify diverse types of UI: Organic Light-emitting Diode (OLED) and Liquid-crystal Display (LCD) displays (DP61 and DP509), sound messages by using beeps and speakers (DP503 and DP515), and dashboard widgets. In line[inline]DataPoint for widgets. We also came across data points that discuss or implement specific components dedicated to operator notifications. For instance, data point DP417 mentions a vocal package providing functionalities for alerting the operator via human-oriented audio alerts.

Reconfiguration of ROS components (23) – ROS systems are distributed and rely on independent components that communicate by exchanging several messages at run-time. Misconfigurations are common in ROS-based systems and usually require fine adjustments and high expertise in the ROS communication middleware. In most cases, the reconfiguration consists of modifying ROS launch files. Another common solution is to release new ROS components after the robotic system is deployed, such as for data point DP258 that adds a battery guard, when the system is updated. Moreover, there are cases where roboticists do not know how to launch a specific component, such as an energy monitoring package. This is the case of data point DP183, where a roboticist asks for help to publish some battery information as ROS messages: “I am trying to do is to create a package that executes some of these functions, for example, to read the voltage of the battery, and publish the data as ROS messages.”

Use of low-powered devices (22) – In many cases, some components of a ROS-based system are deployed on an external Single-board Computer (SBC), as we can see in data points DP46, DP48 and DP244. In the data point DP244, a roboticist asks for help to launch ROS on a low-powered SBC. He says to have chosen ASUS Xtion SBC due to “the lag of enough USB ports and the fact of less energy consumption.” We also observe data points where the discussion heads to other low-powered devices. This is the case of data point DP47, where a roboticist discusses which laser scanner they should use for their robotic project. One of the answers suggests a laser scanner with low power consumption: “many smaller robots use the Hokuyo URG-04LX, which is [...] cheaper, has lower power consumption but also much worse specs than the other two.” The hardware needs to be purchased, and the price may vary a lot depending on their characteristics. For instance, a LIDAR sensor for small projects costs less than €400. Therefore, knowing energy-efficient hardware in advance may also benefit economically.

Software improvements (35) – This family of solutions represents improvements/fixes done exclusively on the software controlling the robot. For example, data point DP84 is a code commit with a few line modifications correcting the robot
behavior since a drone was not considering its battery level while taking off. Another example is the data point DP219, which corrects the battery status since it had not been updated in a graphical dashboard. Note that both codes, before being corrected, may lead to serious energy issues due to wrong energy tracking. As an example of new software, we consider data point DP35, which implements a new $tf\_remapper$ ROS node that according to developers helps to “stop wasting energy and CPU cycles”. This node is used to deal with messages in a bag, a file format to store logged data in ROS. In this data point, the mention of energy waste is among many other technical details, which could have been overlooked without the extensive data analysis we conduct in this work. Moreover, if roboticists do not adopt this module as a pattern, they keep relying on less energy-efficient ones, which as a consequence, might potentially lead to energy waste.

Other notable themes (71) – Other notable solutions that our study reveals are: battery charge or recharge strategies (14 occurrences); the use of energy-efficient sensors (11 occurrences); simulation of real-world scenarios (11 occurrences); the software testing that either identifies energy-related bugs or validates corrections (9 occurrences); recommendation of alternative batteries (8 occurrences); documents that guide roboticists or developers (7 occurrences); deploy services remotely, such as in the Cloud (6 occurrences); and communication improvements, such as via serial ports or networked nodes (5 occurrences). Despite these solutions not being numerous, they are diverse and deserve roboticists’ attention. They comprise existing documentation that can provide information about how to implement new ROS nodes with energy efficiency in mind, together with dedicated software testing and simulation techniques. Moreover, remotely deploying services that assist or control robots is a good strategy since it keeps heavy computation away from the robot and, therefore, improves energy consumption [41].

D. Mentioned quality attributes (RQ4)

In this RQ we investigated whether quality attributes are mentioned in the studied data points. From the 527 extracted data points, we noted that 134 of them (25.4%) mention at least one quality attribute. The most common quality attributes are Usability, Performance, Reliability, Functional Stability, and Compatibility, although Usability is by far the most common one. Due to space constraints, in this section, we will briefly discuss the three most recurring quality attributes.

Usability (78) – Usability is a measure of how easy to use a user interface could be. Mentions to usability in our data points are mostly related to how to better show battery information to the robot operator. This could be achieved by, for instance, when one committer adds a script that highlights when the battery is at full capacity (DP20). Another way to enhance software usability is by providing accessibility. We noted many code changes aimed to use sound to indicate battery status. For instance, the following commit message suggested that “Speak the remaining percentages of the battery if it’s not charged”; this particular pull-request (DP526) was made at the project jsk_robot with this goal.

Performance (18) – Performance is about the process and techniques applied to software systems aimed to improve characteristics such as latency, throughputs or memory usage. In ROS Discourse, one roboticist reported that $tf\_remap$ module is not efficient. As they reported: “Have you ever run a $tf\_remap$ on a complex system with tens of nodes subscribing TF? Have you looked at the CPU utilization? Stop wasting energy and CPU cycles by moving to $tf\_remapper\_cpp$” (DP35). Moreover, we found an issue on a ROS project that aims to convert files to videos to ease visualization. However, to improve the speed of the application (which was very slow in generating animations), ROS committers had to rely on multiprocessing and downsampling. These changes enable considerable speedup (DP73). Similarly, we found a commit that has the intention to disable a module instead of setting it to zero. According to the commit author, the intention was to “avoid excessive power usage after shutdown.” (DP447).

Reliability (17) – Reliability is about performing a task consistently, to function without failure. To prevent that robot battery drains, which would cause the robot task to fail, we observed several discussions on how to make the robot to recharge its batteries autonomously (i.e., docking (e.g., DP206). Docking means that the robot stops whatever it is doing and drives back to a charging station. Answers to this question were highly sophisticated since robots can do a myriad of tasks. For instance, we noticed a pull-request (DP252) that implements a similar procedure. According to the author: “When taking off, if the battery is low, should try to land; When reaching the goal, if the battery is low, should try to land”.

V. Discussion

In addition to the answers to RQ1-RQ4, in our analysis we also noticed recurrent reflection points about the state of the practice on energy-efficient robotics software. Energy-related discussions are rare – Only 0.002% of the 339,563 considered artifacts contained energy-related discussions. This result confirms previous works that also found that these types of discussions are scarce among developers [57]. Managing energy-related issues is not trivial – In a non-negligible number of data points (10 for the causes and 2 for the solutions), roboticists are seeking help about how to manage energy-related aspects of their software. As notable examples, in our dataset roboticists were seeking help for simulating battery usage in the Gazebo ROS simulator (DP42), how to solve issues in the Kinect sensor due to it requiring extra power under some conditions DP115, etc. This reinforces the importance of our study, especially our results for RQ3, which can support even experienced roboticists in solving energy-related issues in their ROS-based systems. Energy consumption should be treated as a first-class quality attribute – In some data points, we noticed that energy consumption is considered after an initial version of the system has been developed. This can be a problem in some
cases since updating a ROS-based system after months of development might not be possible (e.g., underwater robots); this phenomenon can be seen a form of energy-related technical debt. As an example, in DP14 a roboticist claims that “we would love to have low power consumption so that the robot can operate as long as possible [...] I would err towards the more expensive computer for an initial prototype so that you can get something running, and then work on optimizing the software to decrease the computing power required”.

Energy efficiency as a bug – In our analysis, we noticed that in 9 cases energy-efficiency mechanisms were actually the source of bugs and/or unexpected behavior within the system. Those bugs might be difficult to detect since they are linked to energy consumption in non-trivial ways. For example, in DP235 “when the turtle3 burger battery gets low [...] the robot stops moving but the local window [of the SLAM algorithm] keeps moving in the same direction at the same speed until the robot position on the local windows gets to the edge of the global map or over a known obstacle on the global map window”. Also, as mentioned in DP128, some processes might go into sleep mode as an effect of a power save feature, potentially leading to unexpected availability/reliability issues. We suggest roboticists (and researchers alike) carefully reflect on the possible consequences of having energy-saving modes in terms of system availability and reliability.

ROS vs traditional energy efficiency – We noted that developing energy-efficient robots is not the same as developing a traditional energy-efficient app. This is partly due to the natural context of ROS-based software. For instance, robots are intrinsically battery-driven. When performing tasks such as driving or flying, ROS-based software should always monitor energy usage; if the battery is below a certain threshold, the robot should warn the user and/or possibly move back to the dock. This behavior brings additional energy challenges, since constantly monitoring the battery also incurs energy usage. Similarly, auto-docking is not always possible (given how far the robot is from the base). Therefore, managing a robot’s energy consumption seems to be at least as challenging (but perhaps even more) when compared to traditional apps.

Energy bugs in robotics software – Although in this work we do not perform a comprehensive analysis on energy bugs, we did discover some of them when investigating causes of energy-related issues. More interestingly, however, is the fact that these bugs are also domain-specific. We did not find traditional energy bugs such as the loop bug and the no sleep bug, which are among the most common ones in mobile apps. For future work, we leave a fine-grained analysis of energy bugs in robotics software.

UX skills might be on high demand for robotics software – We noticed in our data points that roboticists have to deal with a myriad of different types of UI. Many of our data points are related to improving the way that battery information is presented. Moreover, there also seems to be a lack of usability in ROS-based interfaces, evidenced by the high number of data points targeting this quality attribute. With that in mind, we believe that developers with UX experience would greatly benefit the ROS community.

Robotics software tends to have unique energy-related issues – Other studies in the literature investigated energy-related issues faced by software developers. Interestingly, there is very limited overlap between those and the ones faced by roboticists. For instance, in mobile apps development, recurrent causes of energy-related issues are (i) the misuse of wake locks for keeping the CPU of the device active for long-running tasks and (ii) the actual contents displayed on AMOLED displays, and (iii) networking overhead due to advertisement. Those issues are not mentioned by roboticists when dealing with energy-related issues.

VI. Threats to Validity

External validity – Despite the key role played by ROS in robotics software, its coverage of a large variety of robots, and its vibrant open-source community, we are aware that ROS-based projects may not cover all types of robots. Our population data, however, is diverse (~340k data points, including 10 different robot families and 12 distinct robot capabilities). We extracted these data from multiple projects, covering a large number of contributors, commits, and types of robots. Moreover, we selected the Git repositories for this study from the literature and they already underwent a strict search and selection process, making us reasonably confident of their representativeness.

Our dataset has been built between February and April 2020. Some unsolved energy-related solutions may have been solved after that date, or new energy-related issues might have been reported. Since data from the analyzed repositories are changing constantly, it would be impractical to work on the most recent update all the time. We mitigated this threat by including in our replication package a database with all data points we collected and investigated in this study.

This study reveals that only a small extent of our dataset is energy-related. Nonetheless, we identify 10 energy-related causes and 14 energy-related solutions, which may impact decisions in robotics software engineering. For instance, if software engineers are not aware of the impact of a monitoring rate, they will keep designing energy-inefficient robotics software. Therefore, the scale of the study does not prevent us to identify critical energy-related practices for robotics software.

In this study, we do not consider mailing lists about ROS-based development. We deem this potential threat to validity as acceptable since the main communication channels for developers in the ROS ecosystem are ROS Answers and ROS Discourse. Finally, our study comprises a relatively long period of time (~11 years, i.e., since ROS first releases); to the best of our knowledge, this makes our study the one with the longest considered time span in the ROS domain. Given that in this study we consider multiple data sources, there might be multiple data points about the same energy-related issue. For RQ4, we assume a balance on this software developer behaviour among years. RQ2 and RQ3 are qualitative, so repetitions can help in mitigating inconsistencies in the manual data analysis.
Internal validity – We used a fixed set of keywords to search for energy-related data points while building the dataset (Section II-B). Even if this search strategy requires relatively low effort, it proved to be highly effective in previous studies on energy-efficient software (e.g., [13], [16], [32], [42]). However, we know that it might lead to a high number of false positives and false negatives [9]. We mitigated this potential threat by (i) establishing the search keywords (and related taboo combinations) from the literature on energy-efficient software — see Table I (Phase 1), (ii) manually checking all 5,111 data points resulting from the search and removing all false positives (Phase 2), and (iii) testing that the considered keywords are complete by manually checking a random sample of 400 data points without energy-related terms (Phase 3). Also, three researchers were involved in the phases mentioned above of our dataset construction process, following a known methodological procedure to avoid subjectivity [53]. Moreover, we answered RQ2 and RQ3 via thematic analysis. To mitigate possible biases due to subjectivity in the extraction of the codes and themes, we carefully followed the thematic analysis approach [51]. Three researchers participated in the thematic analysis approach and all emerged themes were jointly revised until consensus was reached. Finally, even though in some discussions the roboticists extensively elaborate on the impact at run-time in their projects, in this study we do not assess whether the emerged causes and solutions of energy-related issues actually impact the energy consumption of the robots. We deem this further investigation as out of scope for this specific study since (i) energy consumption is known to be heavily application-dependent [41] and (ii) a definitive answer would require a dedicated experiment targeting each type of robot discussed in our dataset.

VII. Related Work

ROS-based software engineering research – The growing use of ROS in practice is also reflected by recent scientific publications targeting the ROS software ecosystem. Fischer-Nielsen et al. [22] studied dependency bugs (i.e., bugs that appear when accessing a not available asset) on ROS repositories. Malavolta et al. [31] studied 335 ROS repositories from an architectural standpoint and proposed a set of guidelines for the related software architecture design. Curan et al. [19] created a set of tools aimed at visualizing development metrics on ROS repositories to assess their maintenance health. None of these works, though, try to understand what are the energy-related problems that ROS developers have and how they cope with them, which is the goal of our research.

Energy efficiency in the ROS ecosystem – Our work is not the first investigating energy efficiency in the ROS ecosystem. Swanborn and Malavolta [50] reviewed the existing body of research on energy efficiency in robotics software. They found 17 primary studies in the area. They observed that the first research work in this domain was published back in 1995 [8], although the majority of the selected research works were published between 2012 and 2020. This shows the emerging character of the field. While most of the selected works are related to energy measurements and improvements, none of them addressed the analysis of developers’ contributions on open source repositories. Thus, to the best of our knowledge, our work is the first to investigate how developers writing robot-oriented programs deal with energy issues.

Mining energy-related data points – There is a significant number of research that exploits well-known developer repositories to gather energy-related information. Pinto et al. [42] studied the most popular questions (and related answers) about software energy consumption on StackOverflow. Moura et al. [36] performed similar work, but focused on energy-related code changes, i.e., changes that developers do with the intention to reduce energy consumption. Inspired by the work of Pinto et al. [42] and Moura et al. [36], our work shares some of their research questions, but focuses on the ROS ecosystem. As such, we also expand these two contributions by exploring different Q&A platforms and software repositories.

Further, there are domain-specific research that share similar goals. For instance, some studies focus on mining energy-aware commits in the Android ecosystem [7]: mining energy-aware commits and pull-requests in Android and iOS ecosystems and then building a catalog of mobile energy patterns [16]; or investigating if energy-aware commits have any impact on maintainability metrics [17]. These studies share a common limitation: since they rely on mining techniques, they do not measure the actual energy consumption data, and some of the solutions to energy-related problems might be limited to the understanding of the specific developers. Our work shares a similar limitation, too; however, we believe it has a lesser impact in our case, as the majority of our data points are based on textual discussions, and depend less on code changes.

VIII. Conclusions

Given the significant and increasing energy footprint of robots in various sectors, we analyzed the ROS ecosystem from various open-source channels; we quantified and characterized the main causes, solutions, and possible trade-offs of roboticists’ energy-related issues. Energy-related issues are scarce and the energy consumption is often addressed after delivery; at the same time, roboticists look for help to increase the energy efficiency of their robotics software. The practices resulting from our study offer the first step to help roboticists reuse solutions that already addressed energy efficiency, hence building increasingly-mature know-how about the development of energy-efficient robotics software. Our results also support researchers by providing the first comprehensive overview of the state of the practice on energy-related issues in robotics software. Such an overview can help researchers in identifying impactful research directions for future contributions in software engineering and robotics.

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