Energy Efficiency in Robotics Software: A Systematic Literature Review

Stan Swanborn
Vrije Universiteit Amsterdam, The Netherlands
s.o.swanborn@student.vu.nl

Ivano Malavolta
Vrije Universiteit Amsterdam, The Netherlands
i.malavolta@vu.nl

ABSTRACT

Nowadays, robots are widely used in many areas of our lifes, such as autonomous storage, self-driving vehicles, drones, industrial automation, etc. Energy is a critical factor for robotic systems, especially for mobile robots where energy is a finite resource (e.g., surveillance autonomous rovers). Since *software* is becoming the central focus of modern robotic systems, it is important to understand how it influences the energy consumption of the entire system. However, there is no systematic study of the state of the art in energy efficiency of robotics software that could guide research or practitioners in finding solutions and tools to develop robotic systems with energy efficiency in mind.

The goal of this paper is to present a review of existing research on energy efficiency in robotics software. Specifically, we investigate on (i) the used metrics for energy efficiency, (ii) the application domains within the robotics area covered by research on energy efficiency, (iii) the identified major energy consumers within a robotic system, (iv) how existing approaches are evaluated, (v) the used energy models, (vi) the techniques supporting the development of energy-efficient robotics software, and (vii) which quality attributes tend to be traded off when dealing with energy efficiency in robotics. We also provide a replication package to assess, extend, and/or replicate the study.

The results of this work can guide researchers and practitioners in robotics and software engineering in better reasoning and contributing to energy-efficient robotics software.

1 INTRODUCTION

Mobile robots are widely used in many applications [26]. People can buy intelligent robotic vacuum cleaners or lawnmowers from stores. Some hospitals are using robots to provide quick and safe medicine delivery [12].

Batteries are often used to provide power for mobile robots; however, they are heavy to carry and have limited energy capacity. A Honda humanoid robot can walk for only 30 minutes with a battery pack they carry on the back [4]; energy is the most important challenge for mobile robots. Rybski et al. [34] show that power consumption is one of the major issues in their robot design.

Robots can also be non-mobile, these robots mostly exist in an industrial setting and form the basis of the fourth industrial revolution, also called *Industry 4.0* [24]. Industrial firms contribute to 36% of total global energy consumption and 24% of total CO2 emissions [18]. Energy consumption in the manufacturing sector has been declining since 1998. For instance, in the U.S., the energy consumption in the manufacturing sector decreased by 17% from 2002 to 2010 [36]. Despite these improvements, Fysikopoulos et al. [13] assert that 20% to 40% unnecessary use of energy may still be found in industrial firms. Hence the energy performance of manufacturing systems is a *major area of research* and a concern for many manufacturing companies. According to the IFR Statistical Department [17], the level of automation in the automobile frame- and body construction process was 90%, which implies heavy use of industrial robots in related tasks. Also, Engelmann [11] states that about 8% of the total energy consumption in automotive industries belongs to industrial robots.

The **goal** of this study is to rigorously analyse existing research on energy efficiency in robotics software. For this study, a total set of *683* potentially relevant studies are identified. After the application of a rigorous selection procedure, the set of primary studies consist of **17** studies, which underwent a qualitative analysis. Specifically, we define a classification framework for precisely categorizing research results on energy efficiency of robotics software, and we apply it to the 17 primary studies. Finally, we synthesize the obtained data to produce a clear overview of the state of the art, together with an assessment of the trade-offs considered by researchers when dealing with energy efficiency of robotics software.

The **audience** of this study is composed of *researchers* interested to further contribute to the area of energy efficiency of robotics software and *practitioners* interested to improve the energy efficiency of their robots by adopting the approaches that best fit their project and system under development.

Outline of the paper. The remainder of the paper is structured as follows. Section 2 presents the design of our study, whereas Section 3 presents its results. Section 4 discusses the obtained results and their implications. Subsequently, Section 5 describes threats to validity and Section 7 closes the paper.

2 STUDY DESIGN

This study is designed and carried out by following well-accepted methodological guidelines on secondary studies [22, 29, 39].

A complete *replication package* is publicly available[1] for independent replication and verification of our study. The replication package includes the raw data of our search and selection phase, the raw data extracted from each primary study, and the Python scripts we developed for data exploration and analysis.

[1]https://github.com/S2-group/sustainable-se-2020-replication-package

ASEW '20, September 21–25, 2020, Virtual Event, Australia

ACM ISBN 978-1-4503-8128-4/20/09…$15.00
https://doi.org/10.1145/3417113.3422997

2.1 Goal and Research Question

The goal of this study is to identify and classify the characteristics of existing research in energy efficiency of robotics software. We are interested in the points of view of both researchers and practitioners.

This study considers the following research question.

[RQ1] *What is the state-of-the-art on analyzing and improving the energy efficiency of robotics software?*

This research question aims to answer what the state of the art is for achieving and analyzing the energy efficiency in robotics software. Answering this research question is valuable for researchers and practitioners since it provides a thorough understanding of the available techniques for making robotics software energy-efficient, how they have been validated by researchers in the field, their implied trade offs with other quality attributes like performance and maintainability, etc.

2.2 Search and Selection

The study design is agreed and approved upon before starting the search and selection process. This is meant to prevent personal biases during search and selection, as the *search string* and *selection criteria* are already finalized. This, and more threats to the validity of this report are detailed in section 5. An overview of the search and selection process is given in figure 1.

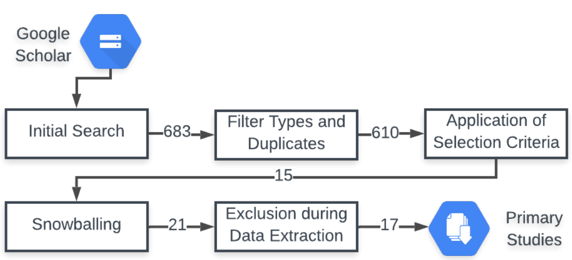

Figure 1: The search and selection process

1. Initial Search: For the initial search, **Google Scholar**[2] was used. Google Scholar is at the time of writing one of the largest and most complete database and indexing system for scientific literature. It has been used as a data source for the following main reasons:

(1) The adoption of this indexer has proved to be a sound choice to identify the initial set of literature studies for the snowballing process [38].
(2) The query results can be automatically extracted from the indexer using Zotero[3].

The results were retrieved using the **search string** as given in figure 2. The search string is kept as general as possible so that potentially relevant studies that would be able to make it to the primary studies, but might not match exactly, are not accidentally filtered out by the automatic search.

[2]https://scholar.google.com/
[3]https://www.zotero.org/

"(intitle:robot) AND (intitle:power OR intitle:green OR intitle:energy OR intitle:battery) AND software"

Figure 2: Search string

2. Filter Types and Duplicates Firstly, we filtered all those studies which are syntactic duplicates (i.e. papers which are exactly the same – same title, same authors). In the case of a semantic duplicate, meaning a paper was published in more than one instance (for example, if a conference paper was extended to a journal version), only one instance has been counted as a primary study. In those cases the journal version of the study has been preferred, as it is supposed to be the most complete; nevertheless, both versions are used in the data extraction phase.

3. Application of Selection Criteria: During this step, the **610** potentially relevant studies are filtered by applying the selection criteria. The study is added to the set of *primary studies* in case it satisfies **all** of the inclusion criteria (*i1-i6*) and **none** of the exclusion criteria (*e1-e5*). These criteria consist of:

- i1 – Studies focussing on robotics.
- i2 – Studies focussing on energy efficiency.
- i3 – Studies focussing on software aspects of the robotic system.
- i4 – Studies providing a certain level of evaluation of the proposed approach (e.g., an empirical assessment, the application to a concrete system, etc.).
- i5 – Studies that are subject to peer review.
- i6 – Studies written in English.
- e1 – Studies that, while focussing on energy efficiency, do not explicitly deal with any software aspect of the robotic system.
- e2 – Studies where energy efficiency is only used as an example.
- e3 – Secondary or Tertiary studies.
- e4 – Studies that are not in the form of a Journal Article, Conference Paper or Book Chapter.
- e5 – Studies not available as full-text.

The application of the selection criteria is done manually. The following steps are performed for each of the **610** potentially relevant studies: (i) read the *Title*, (ii) *download* the study, (iii) read the *abstract*, (iv) read the study *full-text*.

Once the application of the selection criteria is completed for the entire set of potentially relevant studies, a total of **15** papers are identified to satisfy **all** of the *inclusion criteria* and **none** of the *exclusion criteria*.

4. Snowballing: In this phase the automatic search is complemented with recursive *backward* and *forward* snowballing [38]. On completion of the snowballing process, the set of considered studies grew to **21** studies.

5. Exclusion during Data Extraction: Papers that made it to the collection of primary studies can still be removed from the set during the data extraction phase if they are found to satisfy one of the *exclusion criteria* while reading the study full-text. For this literature study, a total of **4** papers have been excluded during data extraction, leading to the final set of 17 primary studies analyzed in this research. The final set of primary studies considered in this research is reported in Table 1.

Table 1: Primary studies of this research

Publication Type	Authors	Title	Year
Journal	Kaitwanidvilai, Somyot; Chanarungruengkij, Veerasak; Konghuayrob, Poom	Remote Sensing to Minimize Energy Consumption of Six-axis Robot Arm Using Particle Swarm Optimization and Artificial Neural Network to Control Changes in Real Time	2020
Journal	Benkrid, Abdenour; Benallegue, Abdelaziz; Achour, Noura	Multi-robot Coordination for Energy-Efficient Exploration	2019
Journal	Rahman, Akhlaqur; Jin, Jiong; Rahman, Ashfaqur; Cricenti, Antonio; Afrin, Mahbuba; Dong, Yu-ning	Energy-efficient optimal task offloading in cloud networked multi-robot systems	2019
Journal	Gürel, Sinan; Gultekin, Hakan; Akhlaghi, Vahid Eghbal	Energy conscious scheduling of a material handling robot in a manufacturing cell	2019
Journal	Xie, Li; Henkel, Christian; Stol, Karl; Xu, Weiliang	Power-minimization and energy-reduction autonomous navigation of an omnidirectional Mecanum robot via the dynamic window approach local trajectory planning	2018
Conference	Cheng, Haoxuan; Sato, Shimpei; Nakahara, Hiroki	A Performance Per Power Efficient Object Detector on an FPGA for Robot Operating System (ROS)	2018
Journal	Hou, Gang; Zhou, Kuanjiu; Qiu, Tie; Cao, Xun; Li, Mingchu; Wang, Jie	A novel green software evaluation model for cloud robotics	2017
Conference	Kim, Jeongwan; Dietz, J. Eric; Matson, Eric T.	Modeling of a multi-robot energy saving system to increase operating time of a firefighting robot	2016
Conference	Wigström, Oskar; Lennartson, Bengt	Sustainable production automation-energy optimization of robot cells	2013
Conference	Licea, Daniel Bonilla; McLernon, Des; Ghogho, Mounir; Zaidi, Syed Ali Raza	An energy saving robot mobility diversity algorithm for wireless communications	2013
Conference	Kırtay, Murat; Oztop, Erhan	Emergent emotion via neural computational energy conservation on a humanoid robot	2013
Conference	Huh, Sungju; Hong, Seongsoo; Lee, Joonghyun	Energy-efficient distributed programming model for swarm robot	2013
Conference	Patel, Sonali; Shukla, Anupam; Tiwari, Ritu	Efficient strategy for co-ordinated multirobot exploration	2012
Conference	Mei, Yongguo; Lu, Yung-Hsiang; Lee, CS George; Hu, Y. Charlie	Energy-efficient mobile robot exploration	2006
Conference	Mei, Yongguo; Lu, Yung-Hsiang; Hu, Y. Charlie; Lee, CS George	A case study of mobile robot's energy consumption and conservation techniques	2005
Conference	Jia, Menglei; Zhou, GuangMing; Chen, Zong-Hai	An efficient strategy integrating grid and topological information for robot exploration	2004
Conference	Barili, A.; Ceresa, M.; Parisi, C.	Energy-saving motion control for an autonomous mobile robot	1995

2.3 Data Extraction

During the data extraction phase, each *primary study* is read full-text and its relevant information is collected by means of a dedicated classification framework. The classification framework is used to collect all relevant data points for each primary studies so to facilitate the similarities and patterns between the primary studies in terms of how they deal with energy efficiency of robotics software. The classification framework is improved in multiple iterations and it has been built collaboratively by two researchers. The classification framework for this study is reported in Table 2.

Table 2: The classification framework

Parameter	Example
Used metric	*Frame rate, Watts*
Application Domain	*Robot Exploration*
Identified Major Energy Consumers	*Physical movements / Inefficient HW*
Evaluation	*Simulation-based, Real-World application, Combination, None*
Energy Model	*1 Unit of Distance = 1 Unit of Energy*
Techniques for Energy-Efficiency	*Offloading computation, limiting idle time, etc.*
QA Trade-off	*Performance Efficiency vs Energy Efficiency*

2.4 Data Synthesis

During the data synthesis phase, the filled out classification framework is used to collect the results and gain insights. More specifically, we carried out a *narrative synthesis* of the results obtained both quantitatively and qualitatively; this step allows us to (i) perform an evidence-based interpretation of the extracted data. Narrative synthesis refers to a commonly used method to synthesize research in the context of systematic reviews where a textual narrative summary is adopted to explain the characteristics of primary studies [30]. These are given in section 3.

3 RESULTS

In this section we report the insights gained from our analysis of the extracted data for each parameter of the classification framework.

3.1 Used Metrics

It can be observed that the metrics used in the primary studies differ significantly. The three most common, descriptive and comparable metrics we observed are:

(1) $FPS^4/Watt$ [10]
(2) $Joules/Meter$ [25]
(3) $Joules/H$ or $Watts/H$ [5, 21]

Moreover, in the case that a simplified energy model is used, the most used metric is the units of distance traveled per units of energy [27, 28].

3.2 Application Domain

In figure 3 it can be observed that the application domain of **Robot Exploration** is the most frequent domain considered in the primary studies. The domain of **Industrial Robot** is in second place with less than half the frequency.

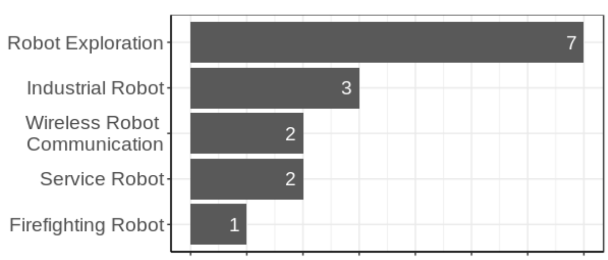

Figure 3: Application domains

This is interesting, considering that in terms of emissions and energy saving potential, there is far more to achieve in the industrial domain as specified in Section 1. From this result we can deduce that so far the main motivation for improving the energy efficiency of robotics software is to improve the functional aspects of the system, rather than its environmental impact. The extension of the operational time of a mobile robot, as a result of the improved energy efficiency, is far more functionally relevant than reducing the energy consumption of an industrial robot; considering the industrial robot has a continuous power supply, energy efficiency is not as functionally important as it will not deliver any functional improvement.

3.3 Identified Major Energy Consumers

As shown in Figure 4, the identified major consumers in the primary studies vary considerably.

No matter the application domain, any identified consumer can always be traced back to a (physical) *hardware* inefficiency, which is solved by improving *software*. Considering robots use software to control their hardware, and the fact that robots exist to satisfy some physical need, this is logical. Within this domain of physical inefficiencies, groups of identified major consumers can be observed; these groups and their frequency among the primary studies are reported below.

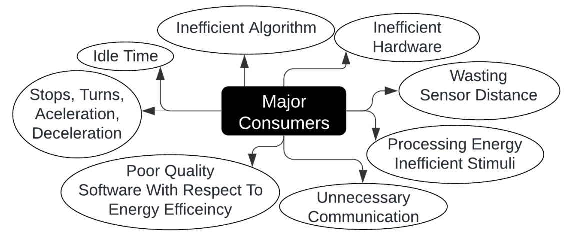

Figure 4: Identified major energy consumers

Inefficient Procedure (11 occurrences): This group considers identified major consumers where the set of actions conducted in the specified manner would result in inefficient use of energy. Some examples would consist of the following:

- The use of a traditional DWA local trajectory planner in combination with mecanum robotic wheels [1].
- An industrial multi-robot production cell using an inefficient scheduler, resulting in significant idle times [37].
- Broadcasting data over a wireless connection from a bad position, resulting in a significantly low channel gain and a lossy connection [25].

Inefficient Movements (3 occurrences): Many papers consider the significant energy consumption of robotic movement. Especially stops, directional changes, the degree to which the direction is changed, and acceleration and deceleration are commonly observed to contribute significantly to the total energy consumption [20, 26, 27, 40].

Inefficient Hardware (3 occurrences): Inefficient hardware is commonly identified to be a major consumer. This category encapsulates those circumstances where the hardware used is inefficient compared to other solutions (e.g., an accelerator for vision-based tracking instead of a more efficient FPGA[5] [10]) or the hardware is used inefficiently (e.g., loss of traction due to a too heavy payload weight [21]).

Finally, from all the primary studies, only one solely identifies software itself as the main consumer [15]. It presents a novel cloud evaluation method; which evaluates the energy efficiency of the software itself. Using the method, the execution of the software itself can be made more efficient. The fact that this is the only study addressing this aspect of robotics software, forms the basis of the discussion in section 4.

3.4 Evaluation

From figure 5, it can be observed that most studies performed an experiment, only one primary study did not. It can be observed that most studies, 9 out of 17, perform an experiment in the form of a

[4]Frame rate (expressed in frames per second or FPS)

[5]Field Programmable Gate Array

simulation, this is without counting the combination of real-world and simulation. Considering those; 12 out of 17 primary studies used a simulation as an experiment. Out of the primary studies, 4 studies performed a real-world experiment and 3 performed a combination of real-world and simulated experiments.

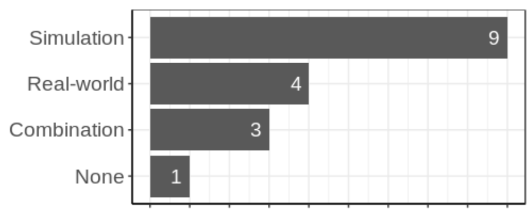

Figure 5: Types of evaluation

3.5 Energy Model

The distribution of the types of energy models among the primary studies is given in Figure 6. Many different energy models have been used among the primary studies, some try to simulate the energy consumption as precisely as possible by simulating drag, torque, acceleration, deceleration, with extensive mathematics and physics equations. These models are called *representational*. Representational energy models are models that can be used in simulations where results would need to be comparable to the real-world. These models are often complex of nature and require extensive information about the robotic system considered, such as friction coefficients (e.g. rolling, sliding and viscous), wheel radius, robot mass, static friction torque, idling power consumption, gear ratio etc. This information is then to be used in accurate physics equations that are capable of modeling the robotic system accurately and representational to the real-world.

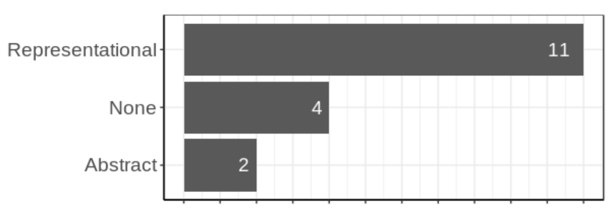

Figure 6: Types of energy models

Opposite from representational models, is the *abstract* model. This model is used in cases where absolute values are not necessary, and only the relevant difference in energy consumption between that which is researched is of importance. The abstract simple model is relevant in use cases where only differences in relevance to one another of that which is researched is of importance. The gathered metrics will be in no way representational and comparable to the real world, but can be used to simply and clearly depict differences with relative credibility. Especially when coupled with results from a real-world experiment, as can be often seen in studies that use such models. An example of an abstract simple model is the grid-based one. The model consists of a simulated grid, where each grid cell consists of 1x1 Units of Distance, and travelling 1 Unit of Distance equals 1 Unit of Energy. Each stop costs 0.5 Units of Energy and each 45° turn costs 0.4 Units of Energy, each additional 45° adding another 0.2 Units of Energy to the total cost. Meaning: a 90° turn would cost 0.6 Units of Energy and a 135° turn would cost 0.8 Units of Energy, etc.

3.6 Techniques for Energy efficiency

The techniques to improve energy efficiency in robotics software vary significantly across the primary studies. Below we report all the techniques extracted from the primary studies.

1 – Offloading computation. The technique to offload computation to other, nearby, robots that are more 'available' (i.e., robots that have more resources available for such computations relative to the current one), or to off-load it to the cloud. The concept here is that the cloud infrastructure (hardware itself, hardware utilization, etc) is more energy-optimized compared to the hardware used on the robots themselves, and will thus result in improved energy efficiency. Even though some energy is wasted in the transmission of data, the overall energy consumption is decreased [33].

2 – Advanced motion algorithm. The technique to improve the motion algorithm, such as path-finding algorithms for mobile robot exploration. The improvement involves incorporating techniques to facilitate energy-efficient movement. Techniques like **3, 4 and 5** can be implemented in an advanced motion algorithm. Like implementing a more advanced obstace-avoidance algorithm, enabling the robot to steer less by steering earlier to avoid the obstacle [40]. Also, many existing studies select the next target based on the utility and cost of the frontier cells [9, 35, 42] However, Mei *et al.* prove that if the next target is selected based on the orientation of the robot, overlap in the robot trajectory is guaranteed to be impossible; reducing energy consumption and reducing the total travel distance [27].

3 – Limiting motion changes. The technique to limit stops, directional changes (turns) and the degree to which the direction is changed as much as possible significantly improves energy efficiency. By the very nature of this technique, an improved obstacle detection and avoidance algorithm is needed for mobile robotic systems [5, 6, 19, 21, 26, 28, 40].

4 – Limiting motion speed. The technique to limit motion at high speeds, with numerous moments of acceleration and deceleration [37].

5 – Limiting idle time. The technique to prevent idle time as much as possible [14, 20, 37].

6 – Limiting unnecessary communication. The technique to limit data transmission by preventing the transmission of duplicate or otherwise unnecessary data in multi-robotic systems [16].

7 – Limiting physical inefficiencies. The technique to limit physical inefficiencies (*e.g.,* loss of traction because of payload weight), if possible, by adding more robots to the system. This technique improved the overall energy consumption as the loss of traction was consuming more energy than the addition of subrobots [21].

8 – Using optimized hardware. The technique to use more advanced hardware (i.e. more energy-optimized, desktop grade, hardware instead of custom robotic hardware) on robots in combination with energy-optimized software [10].

9 – Limiting transmission loss. The technique that sacrificing some energy on finding a better position for the transmission of data over a wireless connection, to increase higher channel gain, will ultimately improve energy efficiency as less time is spend and wasted on (re)transmitting data over a lossy wireless connection [25].
10 – Predicting task's energy cost. The technique to be able to predict the energy cost of any stimuli and reject said stimuli if it is predicted to exceed some energy threshold [23].

3.7 Trade-offs with Other Quality Attributes

In figure 7 it can be observed that the **Performance Efficiency** is the most common QA trade-off with 8 occurrences in the 17 primary studies. Techniques that are similar to techniques **3, 4, 5, and 9**, will inherently decrease Performance Efficiency as it is the only way such techniques improve Energy Efficiency. It should be noted that some techniques, similar to techniques **1, 2, 6, 7, 8**, both improve the Performance Efficiency and Energy Efficiency. It has been observed that this is often the case using techniques that will improve a given physical or software inefficiency. For example, technique **2** improves the path planning algorithm, guaranteeing *no path overlap* during area exploration. It has been proven that this not only improves Energy Efficiency, but it also allows the robot to explore the unknown area faster; thus improving Performance Efficiency [27].

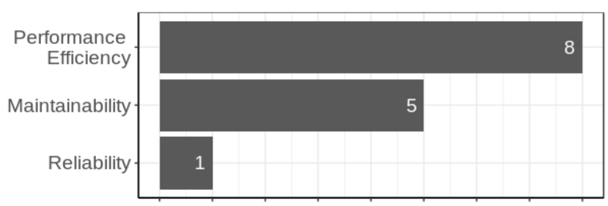

Figure 7: QA Trade-offs

Maintainability trades off with Energy Efficiency in any case where improving Energy Efficiency requires more elaborate and complex software and/or hardware. This is the case for each of the observed techniques, to varying degrees, as the **1 - 10** ones.

Reliability trades off with Energy Efficiency in any case where improving Energy Efficiency requires the system to stop operating for some criteria, like using techniques similar to **10**, or where the chance of operational failure is increased, like increasing the possible points of failure during operation using techniques similar to techniques **1, 7, 9**.

For example, the authors of [20] state that *"[their] method reduces energy consumption from 8155.20 to 7148.6 J, a decrease of 12.3%. On the other hand, the total moving time is increased by 71.8% from 6.60 to 11.34 s"*. In case the system in question can suffer a 71.8% reduction in Performance Efficiency for a 12.3% increase in Energy Efficiency, it might be worthwhile. However, it can be considered a good example of a trade-off which might not be worthwhile for most systems, let alone time-critical systems.

4 DISCUSSION

Insights for researchers. This literature study set out to research the state-of-the-art about improving the energy efficiency of robotics software *itself*. Interestingly, only two of the primary studies were perfectly centered around this topic, whereas other studies mainly deal with how the usage of software impacts other sources of energy inefficiencies (*e.g.,* hardware usage). The publication dates of the two software-centered studies are 2017 [15] and 2019 [33], indicating the infancy of the software-oriented perspective in energy-efficient robotic systems. The importance of such research is significant, considering the high emissions and use of energy in the automation sector, as explained in section 1.

The primary studies are mainly targeting the mitigation of known existing sources of energy inefficiency, be it the loss of traction (physical) [21], the use of an FPGA in combination with a neural network to improve the acceleration on-board (hardware) [10], or the improvement of an inefficient path finder (software) [27]. One could thus say with confidence that, while there is still much to gain from that field of study, the impact of robotics software itself on energy efficiency is not yet sufficiently researched. As our society puts a growing effort towards a sustainable future, it warrants the expansion of software engineering research into this field of study. Also, an improvement in energy efficiency can be achieved by combining all the aforementioned state-of-the-art approaches for improving energy efficiency (see section **??**), with software that is designed to be as energy-efficient as possible. However, objective evidence of such types of claims is still needed.

A good start towards creating energy-efficient software is already going on; a novel green evaluation method for cloud robotics [15]. It enables the identification of bottlenecks in robotics software in terms of energy efficiency, and the prediction of the energy efficiency of a software component at development time. However, the fact that this is the only study, out of 17 primary studies, selected from 683 potentially relevant studies, which explicitly focus on the identification of energy inefficient software, should warrant motivation for the expansion of such research.
Insights for practitioners. The performed literature study identified the set of major energy consumers for the software of robotic systems (*e.g.,* inefficient algorithms, idle time, unnecessary communication). Practitioners can use such a set as *checklist* for ensuring that the main sources of energy consumption are taken into consideration when designing and developing the software of a robotic system. The identified sources of energy consumption have been investigated by independent research groups and in the vast majority of the cases they have been empirically evaluated, thus providing reasonable evidence about their impact on the overall energy consumption of a robotic system.

Moreover, in Section 3.6 we present the various state-of-the-art techniques for improving the energy efficiency of robotics software. Practitioners can use such a set as a catalog of readily-available and empirically-evaluated solutions for energy efficiency issues emerging in their own projects. In this context, it is important to note that the reported techniques should be analysed and applied in context, *i.e.,* by taking into consideration project- and organization-specific requirements. For example, limiting strictly unnecessary communication might be generally applicable, but it might negatively impact either the level of safety of the system (which might benefit from redundant telemetry information coming from the robot) or its usability for end users (who might benefit from the video stream of multiple cameras pointing to the same direction).

5 THREATS TO VALIDITY

Internal Validity. This threat is mitigated by defining the research protocol, as explained in section 2, as rigorously as possible. In order to reduce bias, two researchers iteratively defined and discussed the research protocol after each iteration.

External Validity. The most severe potential external threat to the validity of this literature study is that the primary studies would not be representative of the state of the art on energy efficiency in robotics software. To avoid this potential source of bias, the search strategy applied consisted of both automatic search and backward/forward snowballing [38]. Specifically, the presence of potential gaps left out by the automatic search was mitigated by the snowballing technique. This enlarged the set of relevant studies by considering each study selected in the automatic search, and focussing on those papers either citing or cited by it. Also, only peer-reviewed papers were considered and secondary and tertiary studies were excluded. This potential bias did not significantly impact this literature study, since the considered papers have undergone a rigorous peer-review process, which is a well-established requirement for high quality publications. The inclusion and exclusion criteria were also rigorously and iteratively defined, again discussing it among two researchers, before the study design was put into action.

Construct Validity. This potential bias was mitigated by automatically searching the studies on any data source as indexed by Google Scholar. The search string was also kept general, so to be as inclusive as possible in the automatic search, thus relying on the manual analysis when selecting the papers to be included in this research.

Conclusion Validity. Potential biases during the data extraction process were mitigated by rigorously and iteratively defining the classification framework among two researchers. By doing so, the alignment of the data extraction process with the research question was guaranteed. Furthermore, any potential threats to conclusion validity were mitigated, in general, by applying the best practices on systematic literature reviews in each phase of this study, as stated in [22, 29, 39].

6 RELATED WORK

Brossog *et al.* present a literature survey about energy consumption analysis of industrial robots (IRs) that are used in manufacturing [8]. Similarly to our study, this work identifies relevant consumers of energy (*e.g.,* idle time) and identifies means to improve energy consumption (*e.g.,* energy-efficient motion planning). However, the study significantly differs from ours as it specifically focuses only on IRs and does not explicitly focus on software or its impact on energy consumption.

Bozhinoski *et al.* present a systematic mapping study about safety in robotic systems from a software engineering perspective [7]. The study presents a comprehensive and replicable picture of the state-of-the-art on existing solutions for managing safety for mobile robotic systems. Energy is not considered in this work; the mentioned studies can be used in a complementary manner with respect to our paper by researchers and developers in order to be able to combine safety and energy efficiency techniques for robotic systems.

Ahmad and Babar present a systematic mapping study about software architecture for robotic systems [2]. The work explicitly focuses on software in the context of robotic systems; however, the presented software architectures are not considered with energy in mind. The identified architectures can be used in a complementary manner with this literature study.

Zhi *et al.* present a survey-based study of Multi-Robot Coordination Systems [41]. Their study is aimed at identifying research challenges and problems for robotics. The authors state that a systematic classification and comparison of the problems helps to identify the dimensions of future research in robotics, such as energy efficiency, decision making, and heterogeneous mobile robots. Our literature study complements said future research directions by covering energy efficiency for robotics software.

Albuquerque and Castro present a systematic mapping study identifying and analyzing the existing research progress and directions that influence the elicitation, analysis and negotiation, specification, validation and management of requirements in the robotic systems domain [3]. Our literature study complements this work since energy as a requirement is not considered in their work.

Procaccianti *et al.* present a systematic literature review on energy efficiency in cloud software architectures [32]. The study thus focuses both on software (architecture) and its impact on energy efficiency, it is however considered in a different domain than robotics, *i.e.,* cloud-based systems.

Pramanik *et al.* present a state-of-the-art review of smartphone battery and energy usage, power consumption analysis, measurement, management, and their related issues [31]. It reviews energy but considers the role of software only minorly and in a different domain than robotics.

7 CONCLUSIONS

This study (i) gives an overview of the state of the art on energy efficiency in robotics software and (ii) identifies trade-offs typically associated with the improvements proposed by researchers in the field. Below we report the main insights resulting from this research:

(1) The most common metrics for energy efficiency is energy in Joules, FPS, Watts, Watt/H, in addition to more abstract metrics such as distance travelled per units of energy.
(2) The most covered application domains are robot exploration and industrial robots.
(3) The most common source of inefficiency is the application of inefficient procedures, followed by inefficient movements and inefficient hardware.
(4) The most common way to evaluate the energy efficiency of robotics software consists of performing experiments, evaluating the results.
(5) Techniques for improving the energy efficiency consist of:
  (a) Offloading computations to more energy-optimized infrastructure.
  (b) Improved path finding, obstacle avoidance etc.

   (c) Limit physical inefficiencies, idle time, acceleration, deceleration, stops, turns, directional changes, and the extent of the directional change.
   (d) The use of more energy-optimized hardware on robotics themselves.
   (e) Sacrificing some energy to achieve higher efficiency (e.g. finding a better location with better signal for data transmission).
   (f) Using elaborate software to be able to predict the energy cost of stimuli and reject if necessary.
(6) The most common QA trade-off in order to improve the energy efficiency of robotics software is performance efficiency.
(7) Some techniques will improve both energy efficiency and performance efficiency at the same time, these techniques mostly consist of techniques solving physical and/or software inefficiencies.
(8) Each QA trade-off has varying degrees of impact, depending on the specificities of the system under development.

As future work, we are planning to fill some of the various gaps identified in this research. Specifically, we are working on an empirical study for objectively extracting the architectural tactics applied by roboticists in practice for improving the energy efficiency of robotics software and to perform an empirical assessment of their impact on the robotic system by using real robots in real missions.

ACKNOWLEDGMENTS

This research is partially supported by the Dutch Research Council (NWO) through the OCENW.XS2.038 grant.

REFERENCES

[1] Florentina Adăscăliţei and Ioan Doroftei. 2011. Practical applications for mobile robots based on mecanum wheels-a systematic survey. *The Romanian Review Precision Mechanics, Optics and Mechatronics* 40 (2011), 21–29.
[2] Aakash Ahmad and Muhammad Ali Babar. 2016. Software architectures for robotic systems: A systematic mapping study. *Journal of Systems and Software* 122 (2016), 16–39.
[3] Danyllo Albuquerque, Jaelson Castro, Sarah Ribeiro, and Tiago Heineck. 2017. Requirements Engineering for Robotic System: A Systematic Mapping Study.. In *WER*.
[4] R Aylett. 2002. Robots: Bringing Intelligent Machines To Life. (2002).
[5] A. Barili, M. Ceresa, and C. Parisi. 1995. Energy-saving motion control for an autonomous mobile robot. (1995), 674–676.
[6] Abdenour Benkrid, Abdelaziz Benallegue, and Noura Achour. 2019. Multi-robot Coordination for Energy-Efficient Exploration. *Journal of Control, Automation and Electrical Systems* (2019), 911–920.
[7] Darko Bozhinoski, Davide Di Ruscio, Ivano Malavolta, Patrizio Pelliccione, and Ivica Crnkovic. 2019. Safety for Mobile Robotic Systems: a Systematic Mapping Study from a Software Engineering Perspective. *Journal of Systems and Software* 151 (2019), 150–179. http://www.ivanomalavolta.com/files/papers/JSS_ROB_2019.pdf
[8] Matthias Brossog, Martin Bornschlegl, Jörg Franke, et al. 2015. Reducing the energy consumption of industrial robots in manufacturing systems. *The International Journal of Advanced Manufacturing Technology* 78, 5-8 (2015), 1315–1328.
[9] W Burgard, M Moors, C Stachniss, and F.E. Schneider. 2005. Coordinated Multi-Robot Exploration. *Transaction on Robotics* (2005), 376–386.
[10] Haoxuan Cheng, Shimpei Sato, and Hiroki Nakahara. 2018. A Performance Per Power Efficient Object Detector on an FPGA for Robot Operating System (ROS). (2018).
[11] J Engelmann. 2009. Methoden und Werkzeuge zur Planung und Gestaltung energieeffizienter Fabriken. (2009).
[12] J Evans. 1994. An Autonomous Mobile Robot Courier for Hospitals. *IROS* (1994), 1695–1700.
[13] A Fysikopoulos, D Anagnostakis, K Salonitis, and G Chryssolouris. 2012. An empirical study of the energy consumption in automotive assembly. *Procedia CIRP 3* (2012), 477–482. https://doi.org/10.1016/j.procir.2012.07.082
[14] Sinan Gürel, Hakan Gultekin, and Vahid Eghbal Akhlaghi. 2019. Energy conscious scheduling of a material handling robot in a manufacturing cell. (2019), 97–108.
[15] Gang Hou, Kuanjiu Zhou, Tie Qiu, Xun Cao, Mingchu Li, and Jie Wang. 2017. A novel green software evaluation model for cloud robotics. (2017), 139–156.
[16] Sungju Huh, Seongsoo Hong, and Joonghyun Lee. 2013. Energy-efficient distributed programming model for swarm robot. (2013), 300–305.
[17] IFR Statistical Department. 2010. Executive summary of World Robotics. (2010).
[18] International Energy Agency. Office of Energy Technology and R&D. and Group of Eight (Organization). 2006. *Energy technology perspectives*. International Energy Agency.
[19] Menglei Jia, GuangMing Zhou, and ZongHai Chen. 2004. An efficient strategy integrating grid and topological information for robot exploration. (2004), 667–672.
[20] Somyot Kaitwanidvilai, Veerasak Chanarungruengkij, and Poom Konghuayrob. 2020. Remote Sensing to Minimize Energy Consumption of Six-axis Robot Arm Using Particle Swarm Optimization and Artificial Neural Network to Control Changes in Real Time. (2020), 499–510.
[21] Jeongwan Kim, J. Eric Dietz, and Eric T. Matson. 2016. Modeling of a multi-robot energy saving system to increase operating time of a firefighting robot. (2016), 1–6.
[22] B Kitchenham and P Brereton. 2013. A systematic review of systematic review process research in software engineering. (2013).
[23] Murat Kırtay and Erhan Oztop. 2013. Emergent emotion via neural computational energy conservation on a humanoid robot. (2013), 450–455.
[24] H Lasi, P Fettke, and H Kemper. 2014. Industry 4.0. *Bus Inf Syst Eng 6* (2014), 239–242.
[25] Daniel Bonilla Licea, Des McLernon, Mounir Ghogho, and Syed Ali Raza Zaidi. 2013. An energy saving robot mobility diversity algorithm for wireless communications. (2013), 1–5.
[26] Yongguo Mei, Yung-Hsiang Lu, Y. Charlie Hu, and CS George Lee. 2005. A case study of mobile robot's energy consumption and conservation techniques. (2005), 492–497.
[27] Yongguo Mei, Yung-Hsiang Lu, CS George Lee, and Y. Charlie Hu. 2006. Energy-efficient mobile robot exploration. (2006), 505–511.
[28] Sonali Patel, Anupam Shukla, and Ritu Tiwari. 2012. Efficient strategy for coordinated multirobot exploration. (2012), 105–111.
[29] K Peterson, S Vakkalanka, and L Kuzniarz. 2015. Guidelines for conducting systematic mapping studies in software engineering: An update. (2015).
[30] Jennie Popay, Helen Roberts, Amanda Sowden, Mark Petticrew, Lisa Arai, Mark Rodgers, Nicky Britten, Katrina Roen, and Steven Duffy. 2006. Guidance on the conduct of narrative synthesis in systematic reviews. *A product from the ESRC methods programme Version* 1 (2006), b92.
[31] Pijush Kanti Dutta Pramanik, Nilanjan Sinhababu, Bulbul Mukherjee, Sanjeevikumar Padmanaban, Aranyak Maity, Bijoy Kumar Upadhyaya, Jens Bo Holm-Nielsen, and Prasenjit Choudhury. 2019. Power Consumption Analysis, Measurement, Management, and Issues: A State-of-the-Art Review of Smartphone Battery and Energy Usage. *IEEE Access* 7 (2019), 182113–182172.
[32] Giuseppe Procaccianti, Patricia Lago, and Stefano Bevini. 2015. A systematic literature review on energy efficiency in cloud software architectures. *Sustainable Computing: Informatics and Systems* 7 (2015), 2–10.
[33] Akhlaqur Rahman, Jiong Jin, Ashfaqur Rahman, Antonio Cricenti, Mahbuba Afrin, and Yu-ning Dong. 2019. Energy-efficient optimal task offloading in cloud networked multi-robot systems. (2019).
[34] P.E. Rybski, N.P. Papanikolopoulos, S.A. Stoeter, D.G. Krantz, K.B. Yesin, M. Gini, R. Voyles, D.F. Hougen, B. Nelson, and M.D. Erickson. 2000. Enlisting Rangers and Scouts for Reconnaissance and Surveillance. *Robotics and Automation Magazine* (2000), 14–24.
[35] R Simmons, D Apfelbaum, W Burgard, D Fox, M Moors, S Thrun, and H Younes. 2000. Coordination for Multi-Robot Exploration and Mapping. (2000).
[36] US Energy Information Administration. 2018. Manufacturing energy consumption survey (MECS). (2018). http://www.eia.gov/consumption/manufacturing
[37] Oskar Wigström and Bengt Lennartson. 2013. Sustainable production automation-energy optimization of robot cells. (2013), 252–257.
[38] C Wohlin. 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. *Proceedings of the 18th international conference on evaluation and assessment in software engineering* (2014), 1–10.
[39] C Wohlin, P Runeson, M Höst, M.C. Ohlsson, B Regnell, and A Wesslén. 2012. Experimentation in software engineering. (2012).
[40] Li Xie, Christian Henkel, Karl Stol, and Weiliang Xu. 2018. Power-minimization and energy-reduction autonomous navigation of an omnidirectional Mecanum robot via the dynamic window approach local trajectory planning. *International Journal of Advanced Robotic Systems* (2018).
[41] Y Zhi, N Jouandeau, and A.A Cherif. 2013. A survey and analysis of multi-robot coordination. *International Journal of Advanced Robotic Systems* (2013).
[42] R Zlot, A Stentz, M.B. Dias, and S Thayer. 2002. Multi-Robot Exploration Controlled by a Market Economy. *ICRA* (2002), 3016–3023.