A Systematic Literature Review on Energy Efficiency in Robotics Software

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***Abstract*—*Context*. Nowadays, mobile robots are widely used in many applications. Non-mobile robots are widely used in industrial automation. This literature study covers the field of research into the energy efficiency of robotics software.**
***Goal*. The goal of this literature study is to present an approachable survey of existing research on energy efficiency in robotics software in order to motivate expansions to research the energy impact of the robotics software itself.**
***Method*. The method used is a rigorously designed literature study, spanning 17 primary studies. These primary studies are summarized, categorized, and analyzed in order to derive relevant patterns across the different studies.**
***Results*. The result is given in three parts, as answers to the three research questions. The results show that the field of study, while existing since before the change of the century, is still somewhat immature. With attained interest over the last 5 to 10 years. The results also gave rise to the motivation for expansion of research into the energy impact of the robotics software itself. This field of study is still very much in its infancy but proves essential in maximizing energy efficiency of robotic systems, as software is the main enabler of robotics, its energy consumption will directly influence the energy consumption level of the entire system.**
***Conclusions*. After reading this literature study, the reader will have gained insight in the state-of-the-art of analyzing and improving energy efficiency in robotics software. The reader will be able to judge the findings because of the analyzed publication trends and will be able to judge if the findings are of use for their personal application using the explicate trade-off analysis.**

***Index Terms*—Green Software, Robotics Software, Mobile Robots, Energy Efficiency, Systematic Literature Review, Systematic Literature Study**

I. Introduction

Mobile robots are widely used in many applications [1]. People can buy intelligent robotic vacuum cleaners or lawn mowers from stores. Some hospitals are using robots to provide quick and safe medicine delivery [2].

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 [3]; energy is the most important challenge for mobile robots. Rybski et al. [4] 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* [5]. Industrial firms contribute to 36% of total global energy consumption and 24% of total CO2 emissions [6]. 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 [7]. Despite these improvements, Fysikopoulos et al. [8] assert that 20% to 40% unnecessary use of energy may still be found in industrial firms. That is why 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 [9], the level of automation in the automobile frame- and body construction process was 90%, which implies a heavy use of industrial robots in related tasks. Also, Engelmann [10] states that about 8% of the total energy consumption in automotive industries belongs to industrial robots.

Considering the aforementioned, it is logical to understand that the effort to maximize energy efficiency in robotics will have a significant impact on the world energy consumption and thus CO2 emissions.

The **goal** of this study is to present an approachable survey of existing research on energy efficiency in robotics software in order to motivate expansions to research the energy impact of the robotics software itself. Considering robotics, it is to be expected that the distinction between the physical and non-physical, the software and hardware, is somewhat blurred; *e.g. improving the loss of traction (and thus the loss of energy efficiency) of a robot by its payload weight, by adding sub-robots carrying the payload. Which can only work together with an elaborate, novel, distributed systems algorithm*. This blurred distinction complicated this literature study, as will be apparent in section III, and forms the basis for the motivation for expansion of research into the energy impact of robotics software itself - as explained in section IV.

For this study a total set of 683 potentially relevant studies were identified. After the application of the study design, as described in section II, the set of *primary studies* consisted of 17 studies.

II. STUDY DESIGN

This literature study has been designed and carried out by following well-accepted methodological guidelines on secondary studies, such as those in [11], [12], [13].

This literature study researches multiple research questions. These questions will be given and motivated in subsection II-A. Then the search and selection of papers adhering to the inclusion and exclusion criteria began. This process, and the criteria, are given in subsection II-B. After the selection was made final, these papers are hereon after called the *primary studies*, the summarization and categorization process began. This process is the most important step for writing the literature study; the studies are made comparable by finding the commonalities and patterns in the field of study. This process is further explained in subsection II-C.

A. Research Questions

This study considers three research questions. These questions, their motivations and their metrics are given in this subsection.

[RQ1] *What are the publication trends of papers on energy efficiency in robotics software?*

To be able to judge any characteristics of the state-of-the-art of energy efficiency in robotics software, we need to know the maturity of the field. What kind of publication trends are observed?

[RQ2] *What is the state-of-the-art on analyzing and improving the energy efficiency in robotics software?*

This research question aims to answer what the state-of-the-art is for achieving and analyzing an increase of energy efficiency in robotics software. It also aims to answer what the state-of-the-art is for uncovering aspects negatively impacting energy efficiency in robotics software.

[RQ3] *What are the trade-offs when dealing with energy efficiency in robotics software?*

This research question aims to give insights into what Quality Attributes have been identified to trade-off with energy efficiency. It is valuable for researchers and practitioners to know that if one wants to increase energy efficiency, one can expect a decrease of some other attribute.

B. Search and Selection

After the familiarization process, the *study design* is agreed and approved upon before starting the search and selection process. This is meant to prevent, as much as possible, any personal bias during search and selection, as the *search string* and *selection criteria* are already finalized. An overview of the search and selection process is given in figure 1. The process, as displayed in the figure, is further elaborated on in this subsection.

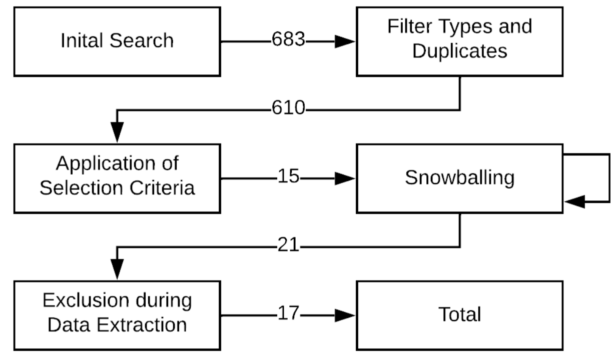

Fig. 1: The Search and Selection process

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

Fig. 2: Search String

1. Initial Search: For the initial search, **Google Scholar**[1] was used. 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 crude, automatic search. The number of results at the time of performing the initial search were **683** potentially relevant studies.

2. Filter Types and Duplicates During this step, all publication types that are not peer-reviewed by nature are filtered out. The potentially relevant studies that resulted from the initial search were thus automatically filtered to be only of any of these types: *Journal Articles, Conference Papers, Book Sections, Books*. By filtering these types, the total number of potentially relevant studies went down to **615**. Then, the filtered collection was filtered automatically once more on explicit duplicates; duplicates that match in *Title* and *Author*. In case a duplicate was found, 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 have been used in the data extraction phase and in the analysis of the publication trends (RQ1, see section III). After the duplicates were removed the total number of potentially relevant studies decreased to **610**.

Note: *this step will only filter easy duplicates (fully matching Title and Authors sections) by design. Any other duplicate*

[1] https://scholar.google.com/

is left to be manually removed in order to prevent unintentional removal. See section V.

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 adheres to **all** of the inclusion criteria (*i1-i5*) and **none** of the exclusion criteria (*e1-e5*). These criteria, in the context of *Robotics Software*, consist of:

- i1 Studies focussing on energy efficiency.
- i2 Studies focussing on software aspects.
- i3 Studies providing evaluation.
- i4 Studies that are peer-reviewed.
- i5 Studies written in English.
- e1 Studies that, while focussing on energy efficiency, do not explicitly deal with any software aspect.
- e2 Studies where energy efficiency is only used as an example.
- e3 Secondary or Tertiary studies (literature reviews, theses etc).
- e4 Studies that are not in the form of a Journal Article, Conference Paper, Book or Book Section.
- e5 Studies not available as full-text.

The application of the selection criteria was done manually by following the steps given below. Each step was performed to see if any selection criteria could be decided based on the information gained by it. If a step decides one of the *exclusion criteria* the next steps are not followed for that particular study, as it already warrants rejection. The following steps were followed for each of the **610** potentially relevant studies:

- S1 Read the *Title*.
- S2 *Download* the study.
- S3 Read the *abstract*.
- S4 Read the study *full-text*.

After this step, a total of **15** papers were identified to adhere to **all** of the *inclusion criteria* and **none** of the *exclusion criteria*. These form the set of **considered studies**.

4. Snowballing: In this phase the automatic search was complemented with recursive *backward* and *forward* snowballing [14]. During the *backward* snowballing, all references of each *considered study* were added to the potentially relevant studies. After each reference from each considered study was added, the steps for applying the selection criteria, as given above, were once more followed. After completing this iteration, each newly considered study was also used in the recursive backward snowballing process.

Following the backward snowballing, *forward* snowballing was used. In this process each study that cites each considered study is added to the potentially relevant studies, hereafter each step for applying the selection criteria was once more followed, and the newly considered studies were recursively used in the forward snowballing process.

On completion of the snowballing process, the set of considered studies grew to **21** studies. These studies now form the *primary studies* set.

5. Exclusion during Data Extraction: During the data extraction phase, each *primary study* if read full-text and its findings are used to construct a data sheet. This data sheet aims to cover all similarities and patterns between the primary studies so that a report can be written, comparing their findings. During this data extraction, papers that made it to the primary studies set can still be removed from the set if they are found to adhere to one of the *exclusion criteria*.

The data sheet constructed during this phase, consists of a set of columns. These columns, example values and their most relevant RQ are given in table I.

C. Summarization and Categorization

Arriving at this step, the set of *primary studies* is finalized, now consisting of **17** papers. After reading all primary studies once more, their data sheets, as given in table I, are filled in manually. Once the data sheet has been fully filled in, the report can be written. The results, as shown in section III, are based on this completed data sheet.

III. RESULTS

As stated in the introduction, section I, this literature study was somewhat complicated. This literature study set out to discover the state-of-the-art of research on the energy efficiency impact of, **explicitly** *robotics software*. Meaning the explicit impact of various aspects of the software itself.

It became quickly apparent during the search and selection process, as described in section II-B, that almost no studies existed on this very specific topic. As of now, of all 683 potentially relevant studies, only two studies have been found that truly research this topic. One study [15] provides proof that a software architectural change; from on-board calculations to off-loading to more available robots or the cloud, actually impacts energy efficiency positively. Another study [16] presents a robotics software evaluation method based on energy consumption. The method allows for identifying those robotics software aspects that consume relatively more energy. It can also be used to predict the energy consumption of a specific piece of robotics software, allowing it to be used during software development, to create more energy efficient software from the moment it is designed.

The fact that these two studies were the only ones truly covering research into the energy efficiency impact of robotics software aspects will form the basis of the discussion, given in section IV. To prevent an insignificant literature study, the focus has been shifted from purely looking at software aspects, to see what impact robotics software in general can have on energy efficiency.

However, as stated in the introduction (section I), the blurred distinction between software and hardware in robotics made the application of the inclusion criteria a tough process. The final selection of primary studies is the result of a rigorous

TABLE I: Data sheet columns.

Column Name	Example Value	Relevant RQ
Date	*2020*	RQ1
Energy Metric Used	*FPS / W (Watt)*	RQ2
QA Trade-off presented	*Timeliness vs Efficiency*	RQ3
Application Domain	*Robot Exploration*	RQ2
Identified Major Consumers	*Too many stops and turns in path*	RQ2
Identified (Software) Aspect Improving Efficiency	*Improved path finder*	RQ2
Major Contribution	*The actual improved, evaluated, path finder algorithm*	RQ2
Experiment	*None / Simulation / Real-World / Combination*	RQ2
Comparison Against State-Of-The-Art	*Yes / No*	RQ2
Energy Model Used	*1 Unit of Distance = 1 Unit of Energy*	RQ2

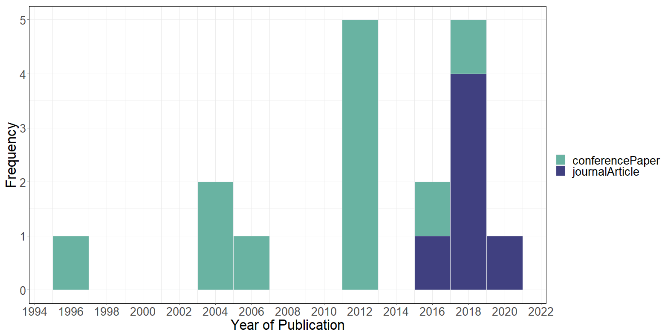

Fig. 3: Publication trends by type

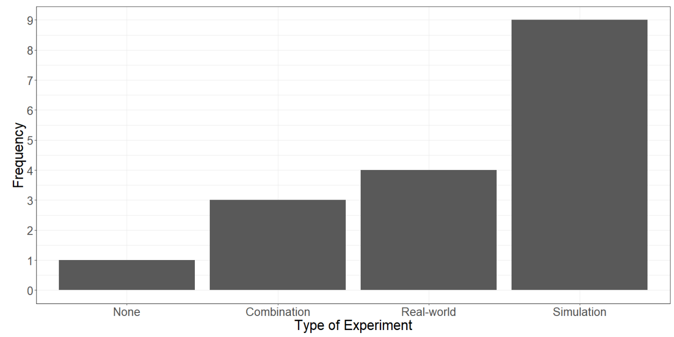

Fig. 4: Experiment distribution

application of these criteria; a study truly had to cover *some* software aspect in relation to energy eff

This section is sectioned according to the research questions. Each section gives a detailed explanation of the findings of this literature study in the context of that research question. The main findings of each research question are presented at the end of each corresponding subsection.

A. Results - publication trends (RQ1)

In this section the results obtained when analyzing the publication trends on energy efficiency in robotics software are presented. Understanding the publication trends in the field of study is essential for interpreting the results of this literature study as it gives an idea of the maturity of the field.

From figure 3 it can be observed that, eventhough this field of study has been around since before the change of the century, it truly attained interest in the last decade (2010 - 2020), with a significant spike nearing 2020.

From these findings we can conclude that the maturity of the field, considering the number of publications before the start of the new century, is rather limited. It is important to take this into account for both the findings of this literature study, presented in the following subsections III-A - III-C, and for the discussion as presented in section IV. Considering the aforementioned difficulty with the initial goal of this literature study; from the publication trends we can see that this is probably the case because of a rather immature field of study.

B. Results - state-of-the-art (RQ2)

In this section the state-of-the-art in analyzing and improving energy efficiency in robotics software is presented as found from the primary studies.

1. Analyzing: The state-of-the-art in terms of analyzing energy inefficiency would be from study [16] in which the authors identify Software as the main component in robotics and thus should also be the main consumer or at least have a significant impact on the total energy consumption of a robotic system. For this the authors developed a method to identify bottlenecks and relatively high consumers in the software of existing systems. For software that is designed with energy consumption in mind, the authors present a method to be able to predict the energy consumption of a specific piece of software.

However, it should be considered that this was the only paper that focussed so explicitly on software and its impact on energy. Considering the 16 other primary studies, we can say that another big standard in this field is the evaluation through practice; in the form of a simulation, a real-world experiment or a combination thereof. From the set of primary studies only study [17] does not feature some form of an experiment. The relative differences in the measurements taken during an experiment give an idea of the energy efficiency of one method compared to another. The distribution of experiment types can be observed in figure 4. It can be observed that a simulation is by far the most popular form of evaluation, used by over 50% of all primary studies. That is not even counting the combination of simulation and real-world experiments, considering these shows that approximately 70% use a simulation as form of evaluation.

An **energy model** is of course needed when simulating the robotic system. For this many different energy models have been used by the various primary studies, some try to simulate the energy consumption as precisely as possible by simulating drag, torque, acceleration or decelleration with advanced mathematics.

However, many papers have been using a simple energy model. A concrete example of this can be found in two papers; [18] and [19]. The first being a study from 2012 and the latter being a study from 2006. These papers are written by different authors but within the same field of study; mobile robot exploration. The model they use 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.

If the problem solved is more global (f.e. the path finder is improved) a simple energy model will suffice. However, when the software presented solves a very local problem, f.e. an improved algorithm for turning a specific type of motor, a more elaborate, mathematically sound energy model is needed.

2. Improving: The state-of-the-art in improving energy efficiency in robotics software is numerous. A trend observed from the primary studies is, however, that they mostly solve hardware (physical) inefficiencies using elaborate software solutions, like an improved algorithm. It is however, by definition, not improving energy efficiency in robotics software. But considering this has been mentioned multiple times, and forms the basis of the discussion in section IV, this section will detail what has been found by studying the primary studies in the context of improving energy efficiency by *using* robotics software in general.

The state-of-the-art in improving energy efficiency in robotics software is numerous, the prime examples are given here. Each primary study presented an evaluated software solution that improves energy efficiency in one specific way. If one would apply all applicable paradigms into their own project, the energy efficiency of the robotic system is guaranteed to be significantly improved. The prime examples consist of:

- The notion of off-loading computations 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 idea here is that the cloud infrastructure is so much more optimized, and will result in an improved energy efficiency. Eventhough some energy is wasted in the transmission of data, the overall energy consumption is decreased [15].

- The notion of improving the path finding for mobile robot exploration. Many existing studies select the next target based on the utilities and costs of the frontier cells [20], [21], [22] However, study [19] proves that if the next target is selected based on the orientation of the robot, that overlap in the robot trajectory is guaranteed to be impossible. This by nature decreases inefficiency and thus improves energy efficiency, it is one of the few studies that presented a solution that both decreased total energy consumption and decreased the total operation time of the robot. This will be detailed further in subsection III-C.

- The notion that limiting stops, turns, directional changes and the degree to which the direction is changed as much as possible significantly improves energy efficiency. By the very nature of this notion, an improved obstacle detection and avoidance algorithm is needed for mobile robotic systems. This notion is widespread over the primary studies, and presented and evaluated in [23], [24], [25], [17], [26], [1], [18].

- The notion that motion at high speeds, with numerous moments of acceleration and decelleration is to be prevented [27].

- The notion that idle time should be prevented as much as possible [28], [29].

- The notion of applying well-accepted Computer Science paradigms, like the popular MapReduce paradigm for distributed systems, to multi-robot systems. Limiting data traffic using MapReduce [30].

- The notion of limiting physical inefficiencies, like the loss of traction, by using an elaborate software solution. Like adding subrobots communicating using distributed systems paradigms [24].

- The notion that the use of more advanced hardware (i.e. more optimised, desktop grade, hardware instead of custom robotic hardware) on robots in combination with optimised software improves energy efficiency significantly [31].

- The notion that sacrificing some energy on finding a better position for the transmission of data over a wireless connection (a higher channel gain) will ultimately improve energy efficiency as less time is spend and wasted on (re)transmitting data over a bad wireless connection [32].

C. Results - energy QA trade-off (RQ3)

From the primary studies it became quickly apparent that no significant improvement of energy efficiency came without the cost to some other attribute. These trade-offs have been mapped to *system Quality Attributes[33]* and will be presented in this section.

This section aims to give insight into the various costs that have been associated with improving energy efficiency. Any reader can judge if any QA trade-off is manageable in the context of their own system, when applying the paradigms described in subsection III-B. The QA's that trade-off with improving energy efficiency are further detailed and related to findings from the primary studies below.

It can be observed from figure 5 that the most common QA to trade-off with Efficiency is **Timeliness**. This is to be expected as one can reason with common sense that when,

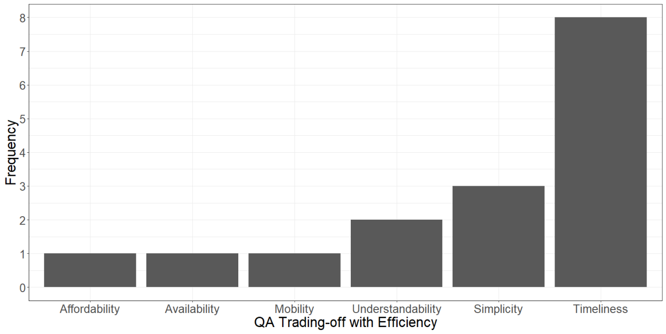

Fig. 5: QA Trade-off with Efficiency frequency distribution

f.e. speed is decreased to increase Efficiency, Timeliness will decrease.

Under Timeliness one could also understand the notion of *Performance*, but considering that this is not an official system's Quality Attribute, it can be explained as Timeliness.

- **Affordability** trades-off with Efficiency as improving Efficiency can require an increase in cost for the developer. For example, the addition of subrobots to reduce the loss of traction by the weight of the payload.

- **Availability** trades-off with Efficiency as improving Efficiency can require the robot to reject stimuli when it predicts that the stimuli will cost too much or waste energy [34].

- **Mobility** trades-off with Efficiency as improving Efficiency can require the robot to limit stops, turns, directional changes and the degree to which the direction is changed as much as possible. This significantly reduces the Mobility of the robot.

- **Understandability** trades-off with Efficiency as improving Efficiency can require the robot to be more complicated in terms of hardware and/or software. The added complexity; like an improved, more complex, algorithm which improves energy efficiency, can reduce the Understandability of the system.

- **Simplicity** trades-off with Efficiency as improving Efficiency can require the system to be expanded in a trivial manner, thus not reducing the Understandability of the system but nonetheless making it more complex. Like adding the aforementioned subrobots to the system.

- **Timeliness** trades-off with Efficiency as improving Efficiency can require the robot to take the longer route instead of the shortest route as the shortest route might contain more stops and turns, which is to be limited as much as possible.

Besides the fact that certain QA's need to be traded-off in order to improve energy efficiency, the extent to which this is required matters just as much, if not more. For each system, the hit to the traded-off QA and the improvement of Efficiency will be significantly different. Thus, an indication of expected percentages cannot be given. However, with common sense it can be reasoned that a disproportional hit to the traded-off QA relative to the increase in Efficiency might not be worthwile.

Study [29] for example states: "This 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 Timeliness for a 12.3% increase in Efficiency, it might be worthwile. However, it can be considered a good example of a trade-off which might not be worthwile for most systems, let alone time-critical systems.

IV. Discussion

This section will motivate the expansion of research into the energy impact of running the robotics software itself. As described numerously in this literature study, this study aimed to give insights into the state-of-the-art of research on the energy efficiency impact of software aspects in robotics software. However, it became quickly apparant after the initial search that such studies were not numerous. Out of the 683 potentially relevant studies, 17 primary studies were selected based on the application of the selection criteria, from which two studies would classify as a study into the energy efficiency impact of the robotics software itself.

Their publication dates are 2017 [16] and 2019 [15], proving the infancy of the field of study.

The importance of such research is significant, considering the high emmisions and use of energy in the automation sector, as explained in section I. This literature study has mainly studied papers improving the energy efficiency of physical inefficiencies, be it loss of traction (physical), the use of an FPGA[2] in combination with a neural network to improve the acceleration on-board (hardware) or the improvement of an inefficient path finder (software).

One could thus say with confidence that, while there is still much to gain from that field, the impact of software itself is mostly left out of the picture. As our society puts a growing effort towards a sustainable future, it warrants the expansion of research into this field of study. The biggest improvement in energy efficiency is going to be achieved by combining all the aforementioned state-of-the-art methods for improving energy efficiency in section III-B, with software that is designed to be as energy efficient as possible. This is already partly possible because of the contributions of [16], however the fact that this is the only paper out of 17 primary studies, selected from 683 potentially relevant studies, which explicitly focuses on the identification of energy inefficient software, should warrant motivation for the expansion of such research.

V. Threats To Validity

Report about each type of threat to the validity of the experiment, according to the classification discussed in class.

A. Internal Validity

This threat has been mitigated as much as possible by defining the research protocol, as explained in section II, as rigorously as possible. Itertivly defining it by discussing it after each iteration with my supervisor[3]

[2]Field Programmable Gate Array

[3]dr. Ivano Malavolta, Vrije Universiteit Amsterdam

B. 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 to happen, the search strategy applied consisted of both automatic search and backward and forward snowballing [14]. 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 exlcuded. 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 with my supervisor, before the study design was put into action.

C. Construct Validity

This potential bias was mitigated by automatically searching the studies on the any data source as indexed by **Google Scholar**. The search string was also kept as general as possible, as explained before in section II-B.

D. Conclusion Validity

Potential biases during the data extraction process were mitigated by rigorously and iteratively defining the data sheet with my superivsor. By doing so, the alignment of the data extraction process with the research questions 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 [11], [12], [13].

This makes this literature study easy to be checked and replicated by other researchers.

VI. Conclusions

To conclude this literature study; the waste of energy by persisting inefficiencies in robotic hardware, software or the physical world (e.g. the weight of payload) can be significantly improved by applying the findings of this literature study as set out in section III, specifically subsection III-B. Despite the improvements in CO2 emmissions and energy consumption over the past years, as mentioned in section I, Fysikopoulos et al. [8] assert that 20% to 40% unnecessary use of energy may still be found in industrial firms.

The unnecessary use of energy can only be significantly reduced by combining the tactics for solving known inefficiencies in the field of robotics, as this literature study has studied and presented as its main findings, with the future research into the impact on energy efficiency by the robotics software itself. The motivation for the expansion into this field of study has been given in section IV and is the most important contribution of this literature study.

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Appendix A
Primary Studies

TABLE II: Collection of primary studies.

ID Publication Type	Authors	Title	Date
1. conferencePaper	Mei, Yongguo; Lu, Yung-Hsiang; Lee, CS George; Hu, Y. Charlie	Energy-efficient mobile robot exploration	2006
2. journalArticle	Xie, Li; Henkel, Christian; Stol, Karl; Xu, Weiliang	Power-minimization and energy-reduction autonomous navigation of an omni-directional Mecanum robot via the dynamic window approach local trajectory planning	2018
3. conferencePaper	Wigström, Oskar; Lennartson, Bengt	Sustainable production automation-energy optimization of robot cells	2013
4. conferencePaper	Cheng, Haoxuan; Sato, Shimpei; Nakahara, Hiroki	A Performance Per Power Efficient Object Detector on an FPGA for Robot Operating System (ROS)	2018
5. conferencePaper	Licea, Daniel Bonilla; McLernon, Des; Ghogho, Mounir; Zaidi, Syed Ali Raza	An energy saving robot mobility diversity algorithm for wireless communications	2013
6. conferencePaper	Kırtay, Murat; Oztop, Erhan	Emergent emotion via neural computational energy conservation on a humanoid robot	2013
7. journalArticle	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
8. journalArticle	Gürel, Sinan; Gultekin, Hakan; Akhlaghi, Vahid Eghbal	Energy conscious scheduling of a material handling robot in a manufacturing cell	2019
9. conferencePaper	Huh, Sungju; Hong, Seongsoo; Lee, Joonghyun	Energy-efficient distributed programming model for swarm robot	2013
10. conferencePaper	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
11. journalArticle	Benkrid, Abdenour; Benallegue, Abdelaziz; Achour, Noura	Multi-robot Coordination for Energy-Efficient Exploration	2019
12. journalArticle	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
13. conferencePaper	Barili, A.; Ceresa, M.; Parisi, C.	Energy-saving motion control for an autonomous mobile robot	1995
14. conferencePaper	Jia, Menglei; Zhou, GuangMing; Chen, ZongHai	An efficient strategy integrating grid and topological information for robot exploration	2004
15. journalArticle	Hou, Gang; Zhou, Kuanjiu; Qiu, Tie; Cao, Xun; Li, Mingchu; Wang, Jie	A novel green software evaluation model for cloud robotics	2017
16. conferencePaper	Mei, Yongguo; Lu, Yung-Hsiang; Hu, Y. Charlie; Lee, CS George	A case study of mobile robot's energy consumption and conservation techniques	2005
17. conferencePaper	Patel, Sonali; Shukla, Anupam; Tiwari, Ritu	Efficient strategy for co-ordinated multirobot exploration	2012

APPENDIX B
DATA SHEET PART 1

TABLE III: Data Sheet Part 1

ID	Energy Metric	QA Trade-off	Application Domain	Identified Major Consumers
1.	Units of Energy	Timeliness vs Efficiency	Robot Exploration	Stops, turns, accelerating, decellerating, sensor distance waste, inefficient algorithm for path finding
2.	Power: Watts (W) Energy: Joules (J)	Mobility vs Efficiency	Robot Exploration	Big change in direction
3.	Joules (J)	Understandibility vs Efficiency	Industrial Robots	Idle time
4.	FPS / W (Watts)	Understandibility vs Efficiency	Service Robots	Inefficient use of robot hardware
5.	J / M (Joules / Meter)	Timeliness vs Efficiency	Wireless Robot Communication	Inefficiency of sending data over bad connection
6.	**NOT GIVEN**	Availability vs Efficiency	Service Robots	Processing of stimuli which costs too much energy
7.	Joules (J)	Timeliness vs Efficiency	Robot Exploration	Inefficient on-board computations instead of off-loading
8.	KiloJoules (KJ)	Timeliness vs Efficiency	Industrial Robots	Idle time
9.	**NOT GIVEN**	Simplicity vs Efficiency	Swarm Robotics	Redudant data transmission
10.	Power: W / h (Watts) Energy: J / h (Joules)	Simplicity vs Efficiency AND Affordability vs Efficiency	Firefighting Robot	Loss of friction due to weight of payload
11.	**NOT GIVEN**	Simplicity vs Efficiency	Robot Exploration	Redundancy / Inefficiency in overlap in paths
12.	Joules (J)	Timeliness vs Efficiency	Industrial Robot	Accelerating, Maintaining Speed, Decelerating, Idle time
13.	Power: W / h (Watts) Energy: KiloJoules (KJ)	Timeliness vs Efficiency	Robot Exploration	Obstacle avoidance without energy in mind
14.	**NOT GIVEN**	Timeliness vs Efficiency	Robot Exploration	Inefficient path planner
15.	NanoJoule (nJ)	**NOT GIVEN**	Analysis	Poor quality software
16.	Power: Watts (W)	**NOT GIVEN**	Analysis	Motion is the major consumer
17.	Units of Energy	Timeliness vs Efficiency	Robot Exploration	More than one robot moving to a target, Robot assigned to target is not most efficient, Robots colliding on their way to targets

APPENDIX C
DATA SHEET PART 2

TABLE IV: Data Sheet Part 2

ID	Identified Improving Software Aspect	Major Contribution	Experiment	Comparison	Energy Model
1.	Improved algorithm, not wasting sensor distance, limit nr of stops etc, target selection based on orientation instead of utility	The improved algorithm	Simulation	Yes	1 Unit of Distance = 1 Unit of Energy. Each stop = 0.5 Units of Energy. Each 45° degree turn = 0.4 Units of Energy, Each additional 45° of turn adds 0.2 units of Energy.
2.	Extended Dynamic Window Approach (DWA)	Extended DWA with Energy Cost	Simulation	Yes	Mathematical Kinematics
3.	Scheduling algorithm reducing idle time	The scheduling algorithm	Simulation	Yes	Page 2 to 4
4.	Use of an FPGA	The complete system; using an FPGA in combination with a neural network	Real-world	Yes	Page 2
5.	Algorithm that would look for a better connection	Elaborate algorithm, finding best transmit location	Simulation	Yes	Page 2 to 4
6.	Trained neural network that would reject such stimuli	The actual trained neural network	Simulation	No	Page 3
7.	Off-loading to cloud or more available robot	An algorithm off-loading to more available robots or the cloud when more efficient	Simulation	Yes	Page 8 to 11 AND page 13
8.	Scheduling algorithm reducing idle time	The scheduling algorithm	Real-world	Yes	Page 3 to 7
9.	Reducing redundant data	Applying distributed systems paradigm MapReduce to reduce redundant data	Simulation	Yes	**NOT GIVEN**
10.	Adding subrobots carrying the weight	The complete system of subrobots, with the distributed systems algorithm to facilitate communication	Simulation	Yes	**NOT GIVEN**
11.	Improved path finder	The improved path finder	Combination	Yes	page 3 to 4
12.	Balancing cycle time with major consumers	Algorithm balancing cycle time with major consumers	Simulation	Yes	page 3 to 4
13.	Trajectory planning with energy in mind	On-board trajectory planning with energy in mind	None	No	**NOT GIVEN**
14.	Improved path planner	Path planner with CostOverflow (CO) added, to get optimal time-energy paths	Combination	Yes	Page 3 to 4
15.	Ability to analyse energy consumption of software	A novel green evaluation method for software	Combination	Yes	**NOT GIVEN**
16.	**NOT GIVEN**	A detailed study, identifying major consumers	Real-world	No	Page 2 to 4
17.	An algorithm preventing given consumers	The entire system, including the algorithm mentioned	Simulation	Yes	Same as study 1