What is the Impact of Releasing Code with Publications?

STATISTICS FROM THE MACHINE LEARNING, ROBOTICS, AND CONTROL COMMUNITIES

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pen-sourcing research publications is a key enabler for the reproducibility of studies and the collective scientific progress of a research community. As all fields of science develop more advanced algorithms, we become more dependent on complex computational toolboxes-sharing research ideas solely through equations and proofs is no longer sufficient to communicate scientific developments. Over the past years, several efforts have highlighted the importance and challenges of transparent and reproducible research; code sharing is one of the key necessities in such efforts. In this article, we study the impact of code release on scientific research and present statistics from three research communities: machine learning, robotics, and control. We found that, over a six-year period (2016-2021), the percentages of papers with code at major machine learning, robotics, and control conferences have at least doubled. Moreover, high-impact papers were generally supported by open-source codes. As an example, the top 1% of most cited papers at the Conference on Neural Information Processing Systems (NeurIPS) consistently included open-source codes. In addition, our analysis shows that popular code repositories generally

come with high paper citations, which further highlights the coupling between code sharing and the impact of scientific research. While the trends are encouraging, we would like to continue to promote and increase our efforts toward transparent, reproducible research that accelerates innovation—releasing code with our papers is a clear first step.

INTRODUCTION

Reproducibility in research is critical to verifying the reliability of scientific ideas and thereby enabling scientific progress. Reproducibility, however, has become increasingly challenging in many disciplines. As an example, optimization is used in many different academic works, but the details of the optimizers are often not shared. Though the choices of libraries and hyper-parameters are usually not necessary to evaluate the novelty of a particular contribution, without these details, it can be extremely difficult to reproduce, verify, adopt, or compare against the original scientific work. Reproducible research is an indisputable cornerstone of innovation.

In recent years, numerous efforts have encouraged reproducibility and open-source code (OSC) in research. For instance, in the machine learning community, where large datasets and software infrastructures are already available,

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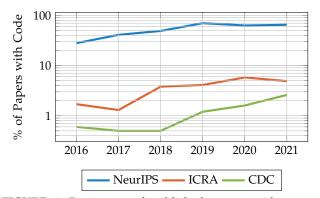


FIGURE 1: Percentage of published papers with opensource code (with logarithmic y-axis) from a major conference in each of the three communities: (1) machine learning: The Conference on Neural Information Processing Systems (NeurIPS), (2) robotics: The IEEE International Conference on Robotics and Automation (ICRA), and (3) control: The IEEE Conference on Decision and Control (CDC).

OSC is becoming common practice (see Figure 1). This trend was especially accelerated by recent reproducibility research efforts (e.g., reproducibility challenges and reproducibility checklists) [1].

Papers with OSC facilitate scientific progress because they are easier to reproduce and benchmark against each other. Coupled with high-quality datasets [2], OSC can shape scientific fields (e.g., the MNIST, ImageNet, and CIFAR-10/CIFAR-100 datasets [3]–[5] in machine learning). These datasets were instrumental to the deep learning revolution of the 2010s and have been collectively cited by over 30,000 research works [6]. In the robotics community, we have seen similar efforts, such as the Robot Operating System (ROS) [7]. ROS provides standardized interfaces for robot experiments, toolboxes [8], and benchmark suites [9], encouraging fair comparisons and improving reproducibility. Moreover, in the control community, the subject of reproducible research has been raised in editorials and workshops [10], [11].

Competitions often encourage OSC and reproducibility. We have also observed a growing number of competitions and challenges at major conferences. The NeurIPS conferences have included competition tracks since 2017; the number of competitions grew from 16 in 2020 to 23 in 2021. Robot challenges have been part of ICRA for over a decade. In 2022, ICRA had a total of ten competitions, including the DodgeDrone [12] and the "Safe Robot Learning Competition" [13] (IROS 2022), that provided fully open-source codebases and encouraged the submission of public code solutions to promote open comparisons and reproducibility.

These past efforts to encourage reproducible research

highlight its importance to scientific progress and form the basis for trustworthy evaluations, comparisons, and further extensions of published results [14]. We must continue to promote and increase our efforts in reproducible and transparent research to accelerate innovation; providing OSC with publications will be imperative to supporting fair evaluation and promoting further research.

In this article, we investigate the current status and the impact of OSC in scientific research. In particular, we present the OSC statistics from three research communities: (i) machine learning, (ii) robotics, and (iii) control. The field of machine learning is leading in data-driven approaches and reproducibility discussions. Publications in this field often rely on a public dataset or simulation environment, and reproducing published results hinge on the availability of adequate computational resources. In contrast, the robotics community heavily relies on algorithmic designs and emphasizes hardware evaluations. Associated publications often require hardware-specific code that often cannot be easily transferred to other research groups' experimental hardware setups. Finally, control is a traditionally theoretic field but is observed to have increased reliance on more complex and data-based techniques that require additional numerical or experimental demonstrations. After presenting the statistics of OSC, we provide insights on the broader impact of code release and include lessons learned for encouraging further efforts to promote reproducible research. We acknowledge that the differences in sharing OSC are partly due to the nature of the research conducted in the three communities, but the diversity also allows us to obtain transferrable insights in developing effective strategies that further encourage reproducibility collectively beyond the specialized domains.

OPEN-SOURCE CODE STATISTICS

To keep the discussion concise, we selected one representative conference from machine learning, robotics, and control theory based on its *h*5-index. The *h*-index estimates the impact of a conference's publication output and is given by the largest number, *h*, such that at least *h* articles from that conference were cited at least h times each [15]. The digit five in h5 indicates that this h-index only considers publications from the last five complete calendar years [16]. For the field of machine learning, we select the Conference on Neural Information Processing Systems (NeurIPS) (Ranking in artificial intelligence: #1 International Conference on Learning Representations (ICLR) with h5=286, #2 NeurIPS with h5=278 [17]). Although ICLR has a slightly higher h5index than NeurIPS, we have chosen to focus on NeurIPS to analyse the machine learning community to remain consistent with previous studies on reproducibility [1]. For the field of robotics, we select the conference with the highest h5-index: the IEEE International Conference on Robotics and Automation (ICRA) (Ranking in robotics: #1 ICRA with h5=116, #2 IEEE/RSJ International Conference on Intelligent Robots and Systems with h5=80 [18]). For the field of control theory, we again select the conference with the highest h5-index: the IEEE Conference on Decision and Control (CDC) (Ranking in automation and control theory: #1 CDC with h5=44, #2 American Control Conference with h5=43 [19]).

Measuring a publication's impact is multifaceted and challenging [20]. For the sake of simplicity, we focus on more readily available metrics that measure the academic impact. A publication's citation count is a frequently used quantity to assess academic impact [20]. For rigorousness, we use citation count data obtained exclusively from Semantic Scholar, as different sources for citation data often provide varying citation counts for the same publication.

The citation count is a cumulative quantity that is typically non-decreasing over time. Generally, publications that have been published later have had less time to collect citations. Therefore, we always compare works published during the same year. However, this does not account for pre-prints released earlier on open-access platforms (e.g., arXiv). We remark that proceeding publication dates typically differ among the selected conferences. Therefore, different citation counts for certain works can also be due to the varying release dates. Finally, the number of citations may also be impacted by the number of conference submissions or, more generally, the size of the specific research community since more conference submissions can vield publications with greater citation counts. We highlight that the numbers of submissions and publications at NeurIPS (2021: 9122 submissions, 2344 accepted [21]), ICRA (2021: 3877 submissions, 1690 accepted [22]), and CDC (2021: 1735 submissions, 1097 accepted [23]) differ.

All data presented in this article was collected from public sources. We have open-sourced the collected data and the associated analysis software that this article is based on [24]. We refer the reader to the appendix for details on the collection process, see Appendix A.

STATUS OF OPEN-SOURCE CODE

In this section, we give an overview of the current status of OSC at NeurIPS, ICRA, and CDC. The percentages of publications with OSC at the three conferences are summarized in Figure 1 (using a logarithmic y-axis). There exists an increasing trend of publications with OSC at NeurIPS, ICRA, and CDC. However, the percentage of publications including OSC varies among the three conferences. For the years from 2016 to 2021, *publications at NeurIPS are ten and twenty times more likely to include OSC compared to publications at ICRA and CDC, respectively.*

We give a more detailed overview of the percentages and total publication count for the three conferences in Figure 2. The percentage of NeurIPS papers containing OSC increased from 27.6% in 2016 to more than 60%

from 2019 onward. NeurIPS has recently made substantial efforts in improving the reproducibility of its publications [1]. We note that between 2018 and 2019, there is a 20.6% increase in accepted publications with OSC. This jump correlates with the NeurIPS reproducibility checklist introduced in 2019 by [1] (see dashed dark orange vertical line in Figure 2 for NeurIPS), which advocated for submitting papers with OSC to allow others to better reproduce their results. The correlation between the steep increase in publications with OSC and the beginning of the NeurIPS reproducibility program implies that this initiative was effective at increasing the percentage of publications with OSC at NeurIPS. Based on our collected data, we find that, from 2016 to 2020, the top 1%-cited publications at NeurIPS included OSC. ICRA has only achieved more than 5% of publications with OSC once, and CDC only recently surpassed 2% of publications with OSC in 2021 for the first time. Although the availability of OSC at ICRA and CDC is not as common, there is also a general upward trend of including OSC with publications for both conferences. In contrast to NeurIPS, ICRA's and CDC's call for papers do not yet explicitly encourage the submission of OSC [25], [26].

SCIENTIFIC IMPACT OF OPEN-SOURCE CODE

In this section, we investigate the impact of OSC for research publications using the collected publication data. To measure the academic impact of OSC in publications, we (*i*) compare the number of citations for publications with OSC and without OSC and (*ii*) investigate the correlation of a publication's OSC popularity with its number of citations.

In Figure 3, we present box plots (outliers not shown) of publication citations at NeurIPS, ICRA, and CDC published from 2016 until 2021, with and without OSC. For NeurIPS, the median number of citations for publications with OSC is always greater or equal to the median number of citations for publications without OSC. We observe that *publications with code get more citations over time than publications without code*. Interestingly, we find that while the increase in the third quartile citation count for publications without OSC reduces to less than 20% after four years since publication, the third quartile count for publications with OSC still increases by 79.13%. This implies that citation counts for highly cited publications with OSC at NeurIPS experience a greater growth rate even six years after publication.

In the last six years since publication, the median number of citations for publications with OSC at ICRA and CDC has typically been greater than the citation count for publications without OSC. This is also true for the third quartile of the citation count for most of the years measured. Unlike the citation statistics for NeurIPS, there is no year-over-year monotonic increase in the median

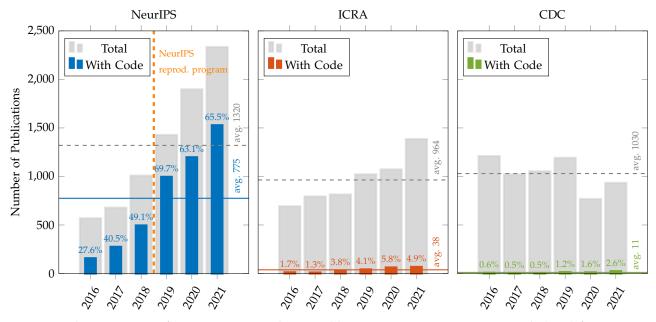


FIGURE 2: The percentages of NeurIPS, ICRA, and CDC publications containing open-source code (OSC) from 2016 to 2021. The percentage of publications with OSC has generally increased over the years (except for NeurIPS from 2019 to 2020, ICRA from 2020 to 2021, and for CDC from 2016 to 2017). However, the magnitude of the percentages varies among the different conferences. The start of the NeurIPS reproducibility program (dashed orange vertical line) [1], which included encouragement of OSC submission in the call for papers, yields an exceptionally high 20.6% increase between 2018 and 2019 for NeurIPS. ICRA's and CDC's calls for papers do not encourage OSC explicitly [25], [26].

and the third quartile number of citations for publications with OSC at ICRA and CDC. We emphasize that the data for both ICRA and CDC for publications with OSC only rely on a few data points (see Figure 2). Therefore, their significance might be limited. However, despite the small number of publications with OSC at ICRA and CDC, the box plots suggest a positive impact on the citation count for publications with OSC.

We also investigated the correlation between a repository's popularity and the associated publication's number of Semantic Scholar citations. A proxy for a repository's popularity is the number of GitHub stars or forks [27], [28]. As the number of stars is typically strongly correlated with the number of forks [27], we chose to only focus on GitHub stars for simplicity. In Figure 4, the number of Semantic Scholar citations for a NeurIPS publication is plotted against the number of GitHub stars, for publications published up to six years ago are shown. We summarized the data using uncertainty ellipses with a confidence value p = 0.99. We used the minimum covariance determinant algorithm by Rousseeuw and van Driessen (1999) to robustly fit the uncertainty ellipses despite outliers [29]. This method assumes an underlying unimodal distribution. Under this assumption, we see that the ellipses' major principal axes for each uncertainty ellipse have a positive slope. This implies there is a positive correlation between the popularity of OSC and its associated publication's citation count. Furthermore, we find that this correlation typically increases with additional years since publication. This positive correlation suggests that *highly-popular OSC* associated with a publication could potentially be one of the factors that increase a publication's citation count and impact.

To summarize, the results in this section highlight the positive impact of OSC and OSC popularity on a publication's citation count—a common measure to assess academic impact.

CONCLUSION AND LESSONS LEARNED

In this article, we investigated the current status and the impact of OSC at premier conferences in three research fields. We found that 60% of the publications at the machine learning conference (NeurIPS) included OSC since 2019. One core factor contributing to these results was the introduction of the reproducibility program at NeurIPS in 2019. We also determined that there is an evident positive trend at robotics and control conferences (ICRA and CDC): the percentages of publications with OSC have at least tripled since 2016 and increased to almost 5.0% and 2.6%, respectively. While the existence of OSC improves reproducibility, we also find that it positively correlates with increased academic impact (as measured by the citation count). Furthermore, the GitHub repository's popularity

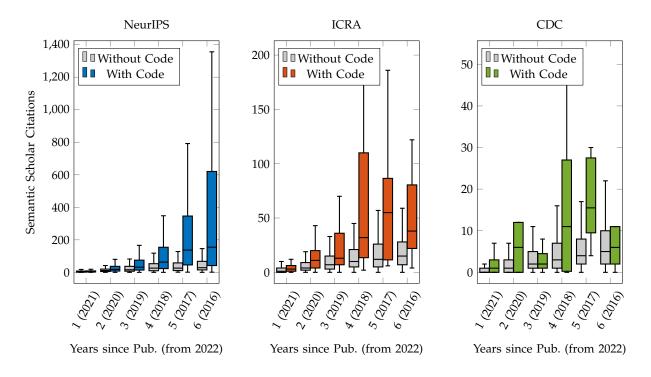


FIGURE 3: Box plots of citation counts for publications at NeurIPS, ICRA, and CDC published in the last six years (2016 to 2021) with and without open-source code (OSC) (with different scales on the y-axis). The median and third quartile numbers of citations for publications over the years since publication with OSC are typically greater than for publications without OSC. For NeurIPS the median and third quartile also increase at a much higher rate for publications with OSC. Due to the small number of publications with open-source code for ICRA and CDC (see Figure 2), it is hard to draw meaningful conclusions.

(as measured by stars) also positively correlates with increased academic impact and typically increases with the number of years since publication.

We believe that *robotic and control theory conferences like ICRA and CDC would benefit from more publications with OSC.* Some obstacles that keep researchers from releasing their implementations as OSC are the additional required effort and risk of releasing erroneous OSC [14]. In light of these barriers, the OSC submission policy has been softly enforced at NeurIPS [30]. This still retains the flexibility for researchers who cannot submit implementations, while encouraging OSC. In addition to the positive academic impacts of releasing OSC with publications determined in this article, the authors in [14] highlight further positive aspects of reproducible research and releasing OSC (e.g. the motivation to conduct analyses at the highest standard and the improved reusability of implementations for the authors themselves).

In the spirit of this article, we published the data and the OSC that we used to analyze it [24]. In the future, we plan to include data from additional years, conferences, journals, and additional code hosting platforms like GitLab and Bitbucket. Finally, we end with a list of lessons learned for improving the reproducibility of scientific work, especially at conferences in robotics and control theory:

- Encourage the submission of OSC: This can improve reproducibility and the impact of the publication as discussed in this article. This could be implemented by adding statements around OSC submission in the call for papers and a submission checklist for authors as presented in [1]. We also suggest that paper submission websites contain specific fields for linking open-source code and datasets.
- 2) Reproducibility challenges: As proposed by [1] for machine learning, these challenges could also be part of graduate courses in control theory (also suggested by [10]) or robotics. Such challenges will provide insight into the reproducibility of publications and increase awareness around open research.
- 3) Unified interfaces: Another channel to promote OSC is to encourage the reusability of the code through unified interfaces. ROS and OpenAI Gym are examples that facilitated code sharing and algorithms comparisons within the respective communities. One valuable next step would be further encouraging

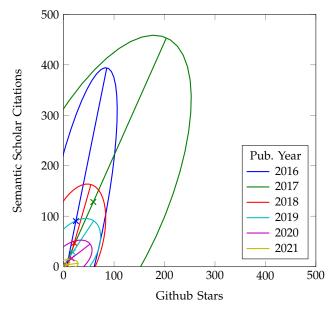


FIGURE 4: The uncertainty ellipses with confidence value p = 0.99 of the number of Semantic Scholar citations for a NeurIPS publication published in the last six years (2016 - 2021) over the corresponding GitHub repository's number of stars. The uncertainty ellipses' area and the steepness of its major principal axis almost monotonically increase with additional years since publication. This highlights that publications with highly popular open-source code tend to be cited more often.

frameworks with structured and standardized interfaces to lower the barrier for cross-discipline adoptions.

4) Releasing benchmarks and hosting competitions: Competitions have been growing more popular at NeurIPS and ICRA. However, at CDC they are only hosted for the first time in 2023. Benchmarks and competitions are great ways to drive novel research ideas and reduce the gap between academic research and real-world application. Defining the right challenges [31]–[34], however, would require closer interactions between academia and industry.

APPENDIX A: CONFERENCE AND CITATION DATA COLLECTION

To systematically collect data and statistics for CDC, ICRA, and NeurIPS, we developed an ad-hoc methodology to suit the different platforms the papers were hosted on being CDC and ICRA papers on IEEE Xplore, and NeurIPS papers on papers.nips.cc.

CDC and ICRA Data Collection Procedure

The conference name, conference year, publication title, first and last author affiliations, keywords, benchmarks,

experimental results, and potential links to OSC were obtained by scraping the HTML from the IEEE Xplore page for each paper. We note that not all conference publications are available on IEEE Xplore. This leads to a discrepancy between the numbers reported by the conference, e.g. [22], [23] and the presented numbers in Figure 2. Should a GitHub link be found, it was then scraped for the number of stars associated with that repository. Finally, citations were scraped by querying the paper title on Semantic Scholar. Data for CDC was collected between August 7– 9th, 2022, and data for ICRA was collected between August 23rd to September 1st, 2022.

NeurIPS Data Collection Procedure

The conference name, conference year, publication title, author names, keywords, and benchmarks were scraped from the publications in the NeurIPS proceedings. Potential links to OSC were scraped by first performing a regex search for github.com and github.io links in the paper. If nothing was found, the paper title was further queried on paperswithcode.com. Finally, for publications from 2021, Openreview.net explicitly lists any OSC released along the paper in a designated field. This information is always used for publications from 2021 specifically. Should a GitHub link be found, its associated stars and forks were scraped. Finally, citation data were scraped from querying the paper title on Semantic Scholar. All NeurIPS data were collected between August 8th to 9th, 2022.

Data Collection Accuracy

Because the data has been collected with automated scraping and processing tools, there are no guarantees that some links to OSC have not been missed or that a publication has not been matched with an incorrect entry on Semantic Scholar. Our implementation mainly focused on OSC hosted on GitHub. Therefore, OSC hosted on other platforms or personal servers could be absent in the statistics provided in this work.

To quantify the accuracy of our method, we compare the percentages provided in Figure 2 with the percentages of camera-ready papers with available OSC provided by [1]. For NeurIPS in 2018, the authors in [1] state < 50%, while we provide 49.1%. For NeurIPS in 2019, the authors in [1] list 74.4% compared to 69.7% shown in Figure 2. This yields an error of 4.7%. The data for OSC for NeurIPS in 2021 was directly pulled from Openreview.net as mentioned above. To the best knowledge of the authors, no other sources state statistics for these quantities. Therefore, the maximum quantifiable error is 4.7%, which is a sizable number of possible implementations not accounted for. However, we believe that these deviations in the statistics generated from our collected data are not significant enough to invalidate the overall discussion and conclusions in this article.

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Angela P. Schoellig is an Alexander von Humboldt Professor for Robotics and Artificial Intelligence at the Technical University of Munich. She is also an Associate Professor at the University of Toronto Institute for Aerospace Studies and a Faculty Member of the Vector Institute in Toronto. She conducts research at the intersection of robotics, controls, and machine learning. Her goal is to enhance robots' performance, safety, and autonomy by enabling them to learn from past experiments and each other. In Canada, she has held a Canada Research Chair (Tier 2) in Machine Learning for Robotics and Control and a Canada CIFAR Chair in Artificial Intelligence and has been a principal investigator of the NSERC Canadian Robotics Network. She is a recipient of the Robotics: Science and Systems Early Career Spotlight Award (2019), a Sloan Research Fellowship (2017), and an Ontario Early Researcher Award (2017). Her team is the five-time winner of the North-American SAE AutoDrive Challenge (2018-21). Her Ph.D. at ETH Zurich (2013) was awarded the ETH Medal and the Dimitris N. Chorafas Foundation Award. She holds both an M.Sc. in Engineering Cybernetics from the University of Stuttgart (2008) and an M.Sc. in Engineering Science and Mechanics from the Georgia Institute of Technology (2007).