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Open access resources to support learning of control engineering

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Abstract— **In recent years the IFAC technical committee has been looking closely at what constitutes an ideal first course in control [16]. Having completed stage 1 of this study, the community is now discussing how to best collate and share the numerous open access resources to support such a course, or indeed more advanced control courses, which staff and students can utilise. A call has gone out to the community to share their knowledge of available resources and this paper gives a preliminary view on the resources that have been proposed so far and ideas on how this information will be shared with the community.**

I. Introduction

Control is a core topic in most engineering programmes ranging from the need for environment control in buildings (civil engineers), to the control of blood sugar levels for diabetes (bioengineers), to the temperature control of a reactor (chemical engineers), to the more typical power grid control (electrical engineers). In consequence, the vast majority of engineering programmes have at least one compulsory control course, typically in years 2 or 3 of the programme. Nevertheless, the most important topics to be covered in these preliminary courses vary somewhat due to different priorities in the discipline and indeed industrial practice in the discipline. This variety was clearly evidenced in the recent surveys [14]–[16] carried out on behalf of the community by the technical committees (TCs) in control education for both IFAC and the IEEE.

Even though a first control course varies in their specifics between engineering programmes, the surveys also gave the community a clear indication of which topics, themes, and skills are common throughout, and therefore, should be prioritised. The summary is not particularly surprising.

1) Some first principles modelling is required since a solid basis in modelling underpins an understanding of control.
2) Most disciplines were likely to use Laplace transform tools in a first course.
3) The main focus should be on helping students understand concepts and motivation rather than theory, albeit some theory is essential to underpin a sound understanding.
4) Laboratories, case studies and industrially relevant issues should be included to ensure good comprehension of the importance of feedback in industry.
5) The use of software tools, to minimise the need for tedious but straightforward mathematics and thus increase focus on understanding, is to be encouraged.

The next step in the project is to collect and organise high quality teaching resources that support staff in their efforts to cover common topics. The focus of these resources are intended to meet the needs of a university education, specifically a first controls course. In the authors' opinion, the availability of different kinds of resources like videos, interactive tools, remote and virtual laboratories, and so forth allows instructors to completely rethink the structure of their own courses [13], especially by taking into account the experience acquired during the COVID-19 pandemic.

Indeed, an appropriate selection of a variety of tools can be organized by the teacher in such a way that the students can learn many concepts by themselves; that is, support the development of core independent learning skills which is something industry and engineering accreditation is very keen on. In the context of on-line learning, such as during the pandemic but moreover often the norm for industrial continuing professional development courses, the availability of high-quality, on-line resources is essential to replace synchronous classes and the critically valuable interactions that happen during them.

Well-designed interactive resources help students become more engaged and provide important feedback opportunities. In addition to the obvious use of virtual laboratory activities, even simple things like on-line quizzes provide valuable learning and feedback opportunities. Hence it is clear that, albeit on-line resources are not quite the same as the interaction possible in face to face teaching, they are a potentially valuable supplement to on-line learning facilitating a more engaging and feedback-rich learning environment.

Additionally, effective and easy access to resources can also have a significant impact on training in industry [2]. Indeed the authors have personal experience of industrialists using online resources, initially aimed at an academic/student audience, to learn fundamental concepts in order to support subsequent practical applications. A curated repository of free online resources could be of utility to practicing engineers who are preparing for licensure examinations, such as the PE Control Systems Engineering exam [11].

Having access to well designed and rigorous resources enables all potential users, irrespective of their motivation,

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to revise and learn by themselves the related concepts and approaches. For example, the physical meaning of the three parameters of a PID controller, as well as the use of tuning rules, can be understood by means of online resources [3], [4] without the student necessarily being part of a structured university course.

As a community, a number of us have produced high-quality resources to support the learning and teaching of control related courses and many of these are freely available to share [1], [3]–[6], [18]. Nevertheless, despite the availability of these resources, one impediment to their wide-spread adoption and use has been the lack of an organised repository where users could search for and obtain the resources easily. Indeed, the IFAC TC9.4 did attempt in the past 15 years to form a repository of resources [20], however, this repository did not seem to meet the needs of the community. An IFAC project over 2017-2020 looked in more detail at how a repository could be developed and maintained, unfortunately with the conclusion in IFAC council that this was unaffordable!

In summary, the need for a repository of learning resources is well accepted, but how to produce and maintain one such has been troubling the TCs for the past 15 years. While the actual organisation and distribution of the resources is still an open question, the TCs in control education for both IFAC and IEEE are preparing for the repository by continuing to collect high-quality resources for a first control course. This paper discusses the latest progress towards this goal and gives a summary of the resources that have been obtained so far. Section II gives some background on early work on forming a repository and the international survey on a 1st course in control. Section III gives an overview of the resources proposed so far by the international community with section IV then discussing some of these in more detail.

II. Background on Repository and Survey

The need for a repository of control education resources is well evidenced by the numerous attempts that individuals have made over the past years.

A. Historical background

In preparation for the IFAC 50 year celebrations, the then chair of the education TC (L. Vlacic) prepared an interim website with a small number of resources and virtual laboratories to support effective teaching [19]. The intention was to garner the enthusiasm of council and build on this, but at the time there was no will to invest the requested funds and thus the website remained largely a private project.

In subsequent years, a volunteer used his own web server to provide the current repository [20]. Although this did receive a number of submissions at the time, it was not particularly user friendly, being more of a database then a smart interface. Partially due to this and partially a lack of effective publicity, this never gained much traction in the community. There was also a general nervousness that a dependence on a single member of the community in terms of both their good will and ability to provide a suitable web server, was not a sensible and sustainable long term solution.

Subsequently (circa 2017), pressure was re-applied to the IFAC hierarchy to consider a more sustainable solution. At the time council was also interested in providing a far more comprehensive database (such as the ARXIV archive), covering the full range of control related resources. However, the conclusions (by 2020) of this were that the provision and maintenance of a suitable web server was well beyond the financial resources of IFAC; and this is also not considering in detail the human resource element required as IFAC largely runs on volunteers.

B. Interim decisions

Having recently completed and published the survey on an ideal 1st course in control [16], it was timely therefore that the TCs on education for IFAC and the IEEE discussed what next during their 2020-21 meetings. These meetings also overlapped with new chair persons for each TC who would bring new visions and priorities. The general consensus was that providing simple and clear guidance to the community on open access resources should be important and the TCs were best placed to facilitate this. However, there was one core difference with previous discussions.

The TCs would provide pointers to suitable resources, but not host them. This simple change means the required website would be far easier and cheaper to manage and maintain. The onus on making the open-access resources accessible and up to date remains with the originator.

The TCs are still discussing the fine detail of how the resources are collated and disseminated and looking at similar solutions such as the Resourcium.org website [5] (Figure 1).

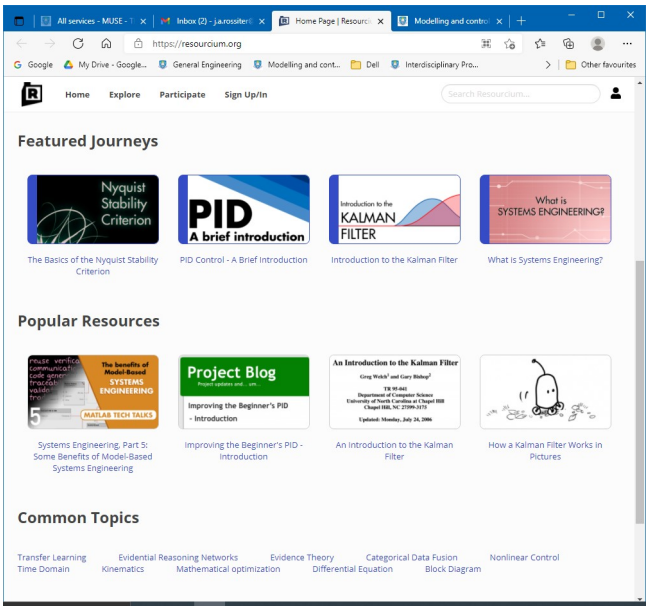

Fig. 1. Home page of Resourcium.org website (Aug. 2021)

C. Survey questions

The first step (current phase) in such a project is to identify and evaluate suitable open-access resources. A questionnaire has been released via Google forms (available at https://tinyurl.com/control-resources) asking for the community to provide information about open-access resources. This survey remains open so that colleagues can continually make content proposals. The survey is deliberately concise with the aim of capturing high level information. Ultimately, the aim is for detailed information to be maintained by the original author on their own website, so the job of the TC is to provide collation and pointing. For each submitted resource, the survey requested the following information.

1) Title for resource.
2) URL address.
3) Indication of topic (from a small subset summarised by: case study, benchmark, measurement and signal processing, feedback basics, modelling, system analysis, control design, discrete, other).
4) Type of resource (laboratory, video, notes, code, etc.).
5) Language.
6) Rules for usage (free, registration, etc.).
7) Additional information.

The remainder of this paper gives an overview of some of the resources that have been offered so far.

III. Early results from the survey

There has been a very encouraging level of response to the survey. As of this writing, there have been 58 resources collected from 45 different members of the community and this section gives an overview of the types of resources that are being offered. A more careful analysis and selection of a suitable platform (such as Resourcium.org or IFAC/IEEE website) for disseminating these results will take place over a longer time scale, but we envisage that more detail will be available for the ACE 2022 symposium, a year hence.

A. Topic and range of contributions

Figure 2 gives an indication of the range of contributions offered and, not unsuprisingly, there are relatively few offerings on what might be considered more specialist or higher level optional topics and far more on the more foundational areas. Some core points are:

- We are pleased to see many case studies offered as these are important for many staff to motivate students.
- More than half of the offerings include system analysis which is probably expected as this will dominate many introductory modules.
- Basic control design and introductory feedback concepts also appear in nearly half of the offered resources.
- As was raised in the earlier survey [16], discrete-time systems are becoming increasingly prominent.

A number of topics appear very little in the analysis of Figure 2, but the reader should exercise some caution here. It is likely that the topics that score low percentages are where respondees selected *other* rather than a pre-filled

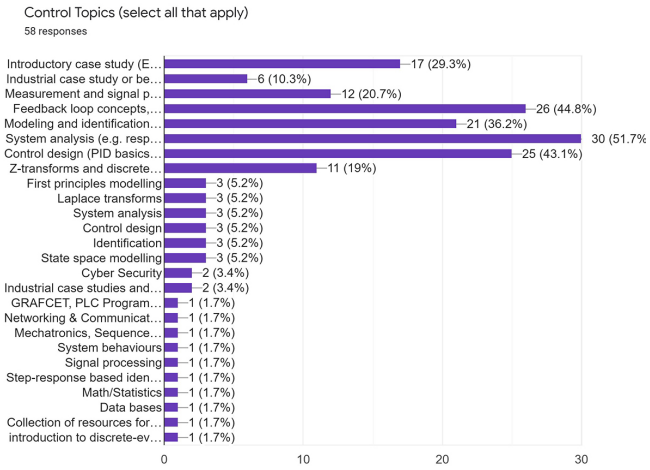

Fig. 2. Topics of contributions (Aug 2021).

category whereas many respondees would have taken topics such as Laplace as being implicitly relevant to a more generic category. A low percentage may be an indicator of a more focussed or narrow resource, perhaps for higher level optional modules.

B. Formats of contributions

The formats of the contributions are summarised in Figure 3. The most common response seems to be video, which is perhaps somewhat surprising but, moreover, a sign of the times. Good pedagogy has long since recognised that video resources are often easier to learn from and engage with than simple text on a page. Indeed the second most common entry is animations, simulations and interactive resources which again suggest the same pedagogical thinking and moreover that such resources are invaluable to the community. Finally there are a substantive number of offerings linked to laboratories and in particular the accessibility of these [4] outside of normal university facilities and this will no doubt be of great interest to many.

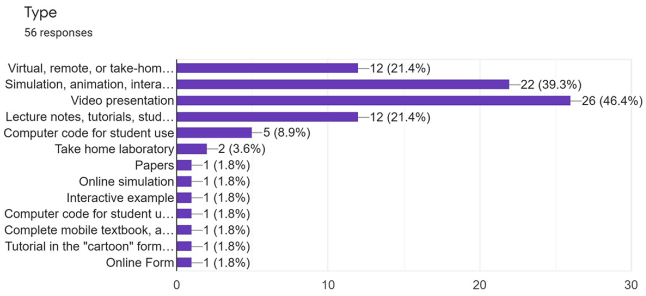

Fig. 3. Formats of contributions (Aug 2021).

C. Rules for using the resources and language

It is implicitly preferable for open-access resources to be offered under a suitable creative commons license, so free to use and edit (with due acknowledgements) and without

the need for licensing. Figure 4 shows that most of the resources meet this criteria, albeit it may be implicit in several that access to commercial software such as MATLAB is useful or even essential. It may also be worth mentioning that the majority of the resources are in English (Figure 5), although not all. In general terms, the use of English would not be an obstacle in many countries and maximises the potential international usage, but it does indicate the need going forward for effective mechanisms to handle resources across a range of languages.

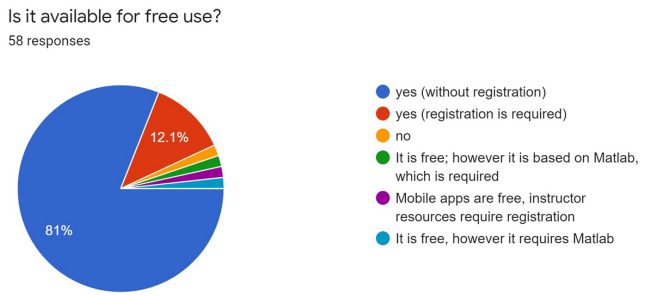

Fig. 4. Availability for free usage (Aug 2021).

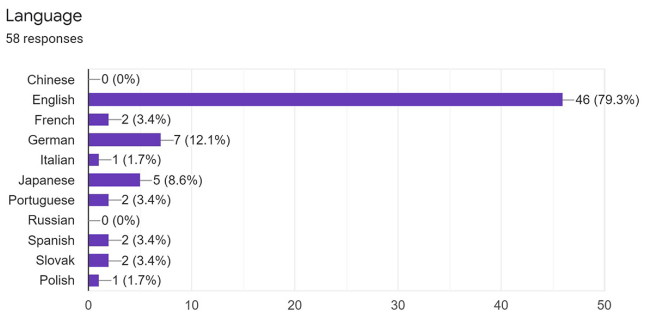

Fig. 5. Language of contributions (Aug 2021).

IV. More detailed discussion of content within some of the resources

It is not possible to discuss all the resources that have so far been proposed, but readers may find it interesting to see an overview of a selected few. We have decided to not include details of resources focussed on more advanced/optional topics as it would be difficult to judge between the many alternatives in the limited space here; these will appear in due course on the proposed website. Similarly, we have not included discussion of resources which are not in English.

The plan is for resources to be organised into topic journeys with short introductions to each, such as in the following website [21]. The control theory map (Figure 6) is a useful overview of the range of topics and their inter-relationships and could form an organisational map for the online resources collected and solicited from the community responses; for clarity content beyond the traditional scope of a first control course is marked with a 'X'. The mapping of the online resources to topics typically covered in a first control course will be completed in the near future and the hope is to have more detailed reporting and discussions at the ACE 2022 event: `https://ace2022.org/`.

A. Laboratories

Virtual and remote laboratories are very popular because they improve accessibility to authentic or pseudo authentic activities and may provide students more extensive opportunities to experiment, and thus learn independently [13]. A number of the resources cover laboratory activity.

The Spanish community is well known for its work on virtual and remote laboratories. Some diverse and interesting activities are provided by the University of Almeria [22], although this page does not highlight licensing/access issues.

The take home kit by Hedengren [8]–[10], [12] is particularly popular, cheap and accessible, requiring either MATLAB or Python [23]. This temperature control lab focuses on simple heat exchanger dynamics, but also includes some dead-time and interaction/disturbances. Code is provided for an extensive range of control and estimation techniques which students can use as is for simple scenarios, or edit for modified scenarios.

B. Video resources

Several authors have provided video resources. These will take time to collate effectively as some seem to be a single standalone resource e.g. [24], [25], whereas others are part of a more extensive series from start to finish in a topic e.g. [26]–[28]. Many of the suggestions are for more advanced materials such as digital signal processing and related materials, e.g. [29]. These will be collated in the longer term for dissemination.

C. Holistic Resources

A few of the resources are more holistic and aim to cover an entire course with a range of learning materials and interaction possibilities such as this one from Valencia [30]. Similar offerings are from Hedengren and aimed more at process engineers [31], an ERASMUS project [32] and Budapest [33].

One of the paper authors has produced his own open access website [17], [18] to support learning across a far more extensive range of control topics and modules, from introductory level up to and including a few more advanced topics (see Figure 7). The website is organised like a text book, so with chapters on set topics: modelling, 1st and 2nd order behaviours, concepts of feedback and basic designs (e.g. PID), advanced analysis and design tools (e.g. bode), state-space, discrete systems, predictive control and use of MATLAB. Each chapter is further organised into sections for ease of content organisation and each section has a number of resources breaking down the learning into bite-size chunks.

A range of resources are provided for the topics and thus, the website could be used as a main resource for a module by pointing to the required sections. A first course would largely use chapters 1-3 and 6 (MATLAB). In summary the website provides the following.

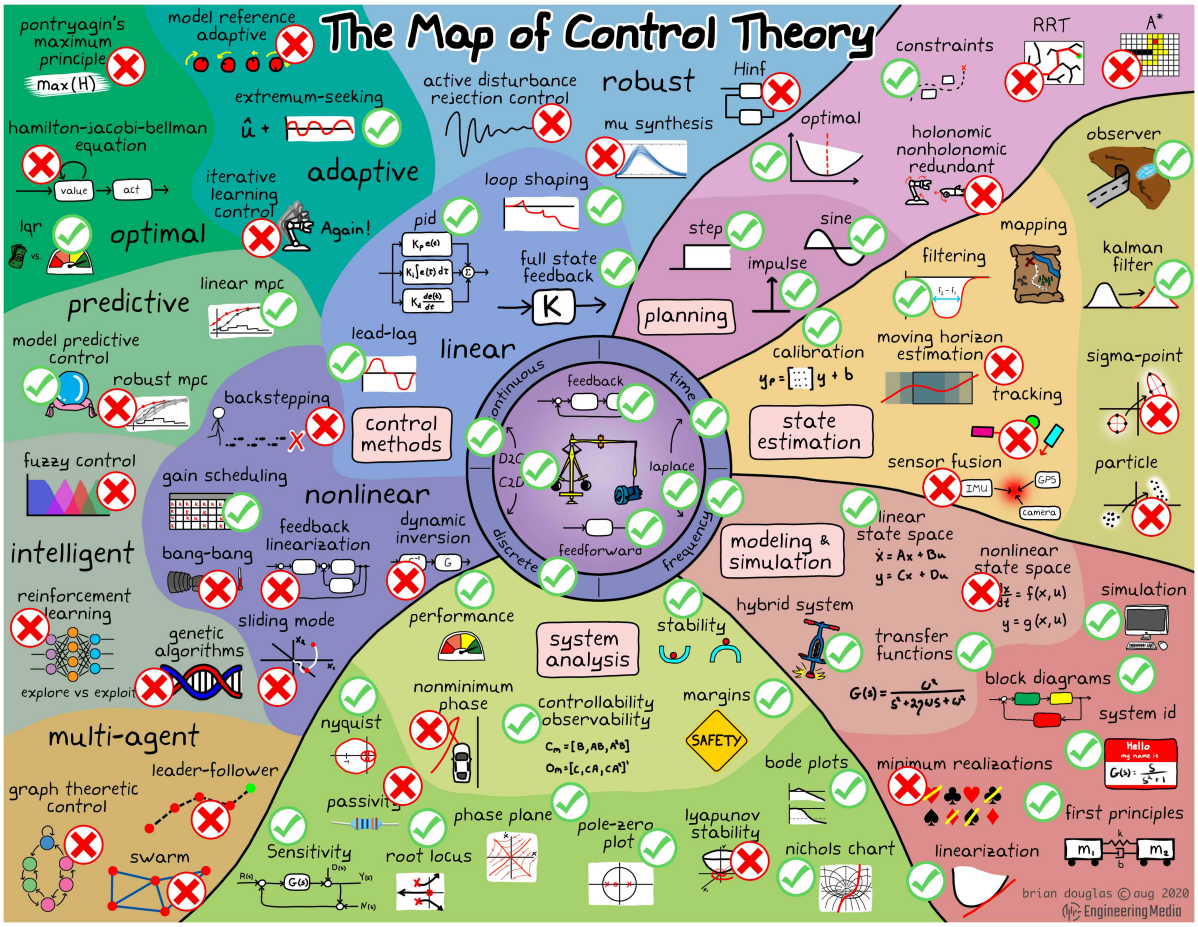

Fig. 6. Map of introductory and advanced control theory topics as an example of grouped topics for organized journeys (`https://engineeringmedia.com`).

1) PDF files (mostly 1-2 sides) on topics.
2) Many topics are supplemented by YouTube videos giving slower explanations of core concepts (these videos are widely used and appreciated in the community). There are also video overviews of chapters and sections to help with capturing motivation and core concepts.
3) MATLAB files, including several GUIs (virtual laboratories) to reinforce learning. Guidance on independent usage and editing to support independent learning are provided for many topics.
4) Tutorial sheets and quizzes.

D. Apps for control

As discussed extensively in the literature [13], [18], MATLAB is a convenient tool to produce virtual laboratories; these are easy to share with the only constraint being that the students need access to MATLAB. Consequently, a group from Stuttgart have produced a number of simple MATLAB apps to support learning of some control design techniques such as loop shaping [7], see [34], [35]. Several authors have provided similar resources, for example [36]–[39].

In a similar vein, Quanser hardware is popular in many university laboratories and the corresponding development team has produced a set of apps and resources that can be deployed on a mobile phone, and thus very accessible [40]. Likewise, MathWorks provides a number of resources of its own which need little publicising [41].

An even more accessible app-like resource, needing only a web browser is provided for simple PID design [42].

V. Conclusion

It is encouraging that so many submissions to the survey on control resources have already been received and we hope that even this brief overview provides helpful links and ideas to readers. The project is intended to be collaborative, so rather than receiving criticism, the coordinators would prefer advice and support, that is, more volunteers to contribute to shaping this project for the community.

The next phase of the project will be collation and dissemination of the resources suggested and consequently we need a suitable low cost, easy to manage but clear web page design. We hope to have more information on this to report by the date of the conference. One core question to ask is how should the resources be categorised?

1) It is clear that we could have a list of topics/themes such as PID and Laplace.

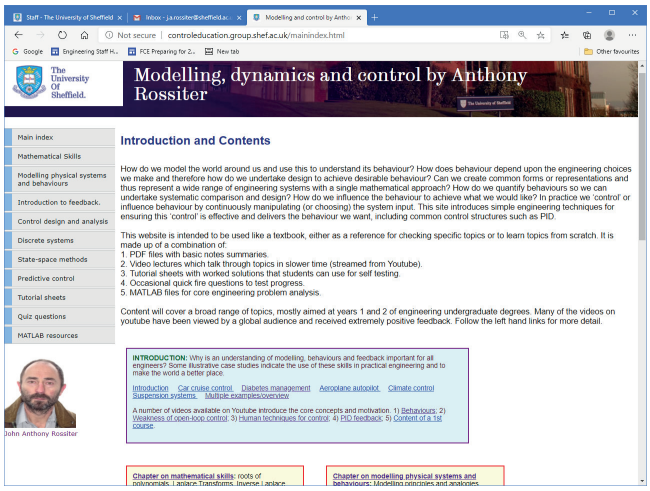

Fig. 7. Home page of website by J.A. Rossiter (Aug. 2020).

2) Potentially there could be a categorisation based on level such as first course, second course, advanced/specialisation.
3) The type of resource (PDF, video, laboratory, ...) is also an obvious categorisation.
4) Licensing (free to use, to edit, registration or software required, etc.).

In the authors' view, there is an important balancing act in having few enough categorisations so that potential users are not over-whelmed, but sufficiently detailed to allow efficient searching and focus to the required resources.

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[25] (https://youtu.be/XaA9UwHE0yg)
[26] https://www.youtube.com/channel/UCMBXZxd_j6VqrynykO1dURw, YouTube Channel: John Rossiter.
[27] https://www.youtube.com/c/VictorLavrenko/playlists, YouTube Channel, Victor Lavrenko.
[28] https://www.youtube.com/channel/UCq0imsn84ShAe9PBOFnoIrg, YouTube Channel, Brian Douglas.
[29] https://youtu.be/hVOA8VtKLgk
[30] https://www.edx.org/es/course/dynamics-and-control
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