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Developing a novel MATLAB control toolbox for encouraging student engagement

John Anthony Rossiter
Department of Automatic Control and Systems Engineering
University of Sheffield
UK
j.a.rossiter@sheffield.ac.uk

***Abstract*—The numerous toolboxes within MATLAB [12] to aid student engagement and learning largely require deep understanding of coding, as well as the associated engineering. This paper discusses some work in progress which is focussing on developing files and resources for a control 101 course [17] which are both engaging and also have much lower pedestals of understanding before use. The intention is focus on attracting student interest and communicating core concepts before students need to begin the longer process of deep learning. Thus this toolbox fills a large gap in the current provision.**

Keywords – Virtual laboratories, independent learning, visualisation, livescripts.

I. Introduction

This paper focuses more on the concept of motivational tools leading to learning, rather than resources focussed primarily on learning. Within the global control community, and partially driven by initiatives such as CONTROL 2030 (report to be published early in 2023, [3], [23]) sponsored by the IEEE, there is a recognition that we need to communicate better with the general public across all age ranges. Why is control important and what are the societal level challenges that control experts can help tackle? In order to to do this, we need a range of resources to capture peoples' attention and to entice them into reflection on what types of skills they would need to help tackle those problems?

Of course the previous paragraph sets out a large challenge which will require a community wide action. This paper focuses on a small part of that challenge and is linked more closely to engineering undergraduates: how do we enthuse undergraduates about the relevance of control and thus encourage them to consider taking higher level courses which will upskill them sufficiently to tackle these future societal level challenges?

A typical historical *first course in control* [2], [16]–[18] has been rather mathematically heavy and a typical anecdotal comment from graduates indicates that they failed to grasp any sense of what control was really about and rather simply learned a number of mathematical procedures in a rather formulaic way. In other words, we as a community failed them. Recent community wide discussions [17], [21], [23] indicate there is a growing recognition in the community of the need to redress this balance. Perhaps a first course should be less worried about rigour and mathematics and instead focus on communicating the core challenges and opportunities and why these are important? Building from there, some relevant technical content can be included.

The challenge for university staff could now be considered to be twofold:

1) How should we update our control curriculum?
2) What learning resources do we need [20]?

This paper concentrates on the latter of these and in particular considers computer based resources which students can access through the web or bespoke software. The paper is organised as follows. Specifically, this paper proposes a new MATLAB toolbox containing a range of engaging and easy to use resources which staff and students can use both to motivate the need for feedback and also to begin learning core concepts.

Section II looks at virtual laboratories in general terms and the role they can play in education. Section III looks at the app environment in MATLAB [12] and why this is convenient for producing virtual laboratories. Section IV then demonstrates some of the proposed resources alongside a vision for future developments. The paper finishes with conclusions.

II. Virtual laboratories

Over the past 20 years or so, the growing capacity of computers has led to an increase in the potential for effective online learning resources. This paper is particularly interested in resources with animation, movement and user interaction or decision making.

A. A brief contextual history

Within the control community, there was an initial push by IFAC (www.ifac.org) around 2006 to produce a repository of learning resources available through the web, in time for the 50 year anniversary. This original project was led by Ljubo Vlacic and produced a personal website which included a number of simple animations and virtual laboratories. The intention had been to gain IFAC financial support to grow this and move it to a more sustainable footing. However, IFAC simply did not have, and still does not, the financial resources to support this in anything beyond a superficial way and largely relies on the community to do these things using their own finance. This

Thanks go to Mathworks who are supporting this project.

stance was reaffirmed recently following an extensive IFAC investigation into the potential and costs of them maintaining a webserver for *useful control resources*.

A few years later, the IFAC control education committee moved the existing, and minimal repository to a slightly more professional website [11], but this was little used and certainly not attractive to non-academic users. Hence more recent pressure has moved towards finding a more sustainable alternative such as the exemplar given in [8]. Here the website acts solely as a pointer to resources which are hosted elsewhere (by the authors) and, as far as the website owner is able, tries to package and organise resources to help users identify learning journeys through these resources and so forth. This project and vision is still in development and the relevant technical committees of the IEEE and IFAC are keen to progress this.

A useful summary of this status is that the onus has to some extent passed back to individuals to provide the most effective resources they can, perhaps just a few each. Through effective sharing and coordination this will then provide a much bigger suite of useful resources to the world.

B. The focus on virtual laboratories

Web based resources cover a wide variety for forms such as notes, videos, audios, virtual/remote laboratories and code. However, the development of virtual laboratories has been a strong theme in the control community for the past 20 years and more, such as the early variants produced by Prof. Vlacic and more commercial possibilities [4], [9], [13]. Amongst these are two strands worth particular discussion here.

Virtual and remote laboratories are particular important because they fit neatly into a popular pedagogical tool [1] which has been called tri-lab. In essence students have:

1) Pre-laboratory activities to engage with the topic, perhaps involving some experiments on a remote/virtual laboratory.
2) Attend the laboratory and collect data.
3) Post-laboratory activities, perhaps involving more experiments on a remote/virtual laboratory.

We discount further discussion of remote laboratories (e.g. [22]), while recognising the value they have, due to the well known complexity and cost of ensuring these are robustly available to large numbers of students. These require suitable infrastructure and support at institution level.

The Spanish community has been particularly active in the development of web-based virtual laboratories, most recently run using a tool called sysquake [5]–[7], [10]. In the main these have been focussed on technical learning outcomes so for use by students actively trying to master particular skills such as root-loci, PID design methods and so forth. The particular selling point of these tools is that, in principle, they run on a browser without the user needing access to specialist software and thus are highly accessible. The disadvantage is more for the academic user as the author is required to master the use of the sysquake tool before they can begin to create resources of their own and this is a little more difficult than more traditional coding tools in the community such as MATLAB [12].

Other authors have decided to base their developments on software that is readily available to the students and thus, requiring students to have this software on their laptops is not an impediment. It is common for Universities to cover the license fees for their students. A popular international choice[1] is MATLAB because:

1) This is the most widely used software in the control research community and thus academic staff are familiar with it.
2) It has a number of toolboxes and functionality that are targeted at control topics, thus minimising the coding required to do advanced analysis, evaluation and design.
3) It has an environment designed for the development of virtual laboratory type activities e.g. [14], [15].

More recently, Mathworks have stopped active support of the original GUIDE environment for virtual laboratories and introduced a more robust environment which we will call *the app environment* [19]. The rest of this paper considers a new project (https://controleducation.sites.sheffield.ac.uk/matlabresources/community-control-toolbox) which aims to exploit this environment to provide a comprehensive virtual learning experience for both students and those we may wish to inspire to study control.

III. The app environment in MATLAB

The app environment is intended to be simple to use for people with some technical know how, but non-coding specialists. The hope is that the average academic can relatively quickly and easily provide an interface that students can engage with which is pseudo authentic and thus helps them relate their learning to real life scenarios.

A. Creating the interface

Figure 1 shows a simple example of an app being created. The user can drag typical blocks from the left into their window, size using the mouse, and then use the settings in the bottom right window to define things such as colours, fonts and so forth. Hence, the first step for the author is to plan what they want their interface to look like and what selections they wish users to make.

With more experience it is possible to use grids and other tools to ensure scaling properties of the interface and consistent sizing and so forth, but such details are not important for this paper.

B. Coding the app

In order to code the app it is assumed that the author has basic familiarity with the MATLAB coding environment; this is relatively conventional and very forgiving so unlikely to be an obstacle. There are two main options for coding functionality:

1) The user creates subfunctions to do specific tasks/computations relevant to the underlying

[1]We accept some universities do not subsidise this, so the reach is not universal. However, we are looking at the MATLAB webserver tools as a means of overcoming this issue.

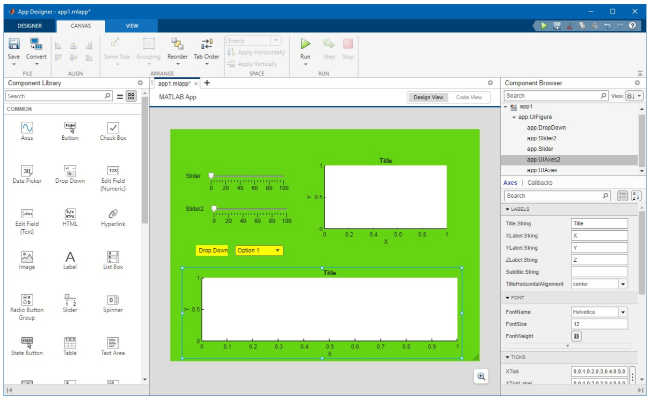

Fig. 1. Example of a the editor environment for APPs.

engineering (Figure 2). These can automatically be accessed from anywhere within the app. To create these use the option in the top left and the environment will manage data transfers and other details for you (again subtleties not discussed here).

2) For items in the window, create callbacks (that is subfunctions) which act when the user interacts with that item (Figure 3). Again, the enviroment automatically handles data transfers and subfunction naming to make this as easy as possible.

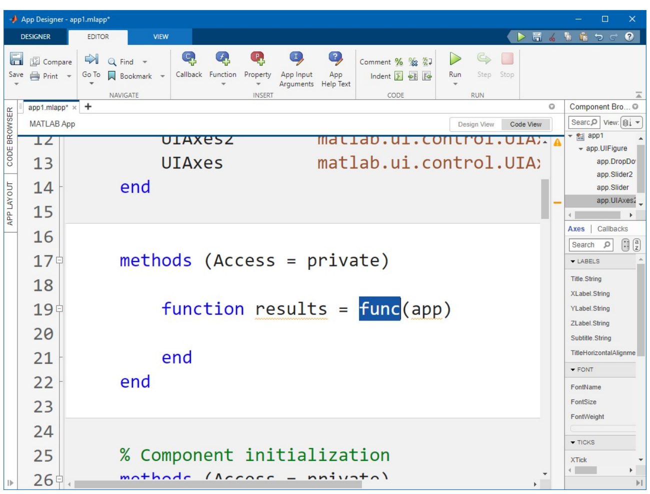

Fig. 2. Create and code a subfunction within the app.

It is also worth noting that the structure variable *app* is automatically carried into all functions and so the easiest way to ensure data is visible within any subfunction is to update app as required. Variables are added to this structure either by direct coding or left hand toolbar selections and appear at the top of the file. This variable also automatically contains handles for all the interface objects such as the axes, sliders and so forth and thus these can be modified directly with simple code such as:

app.Slider2.Value =4 Moves Slider 2 to 4.
hold(app.UIAxes,'on') Hold on for the axes with handle

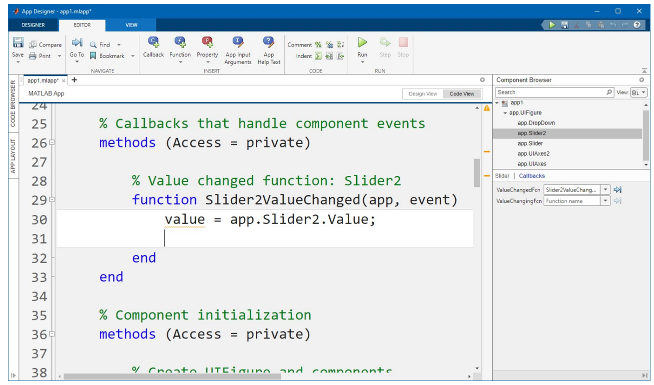

Fig. 3. Create and code a callback subfunction within the app.

UIAxes.

C. Summary

With minimal training, a typical engineering academic is able to code the app environment quickly and effectively. This means that effective resources can be produced in reasonable time without computer scientist expertise, and thus typical academics are empowered to create learning resources that previously would have been too expensive or time consuming to do. As the app sits within MATLAB, the subfunctions can utilise all the associated built in code, toolboxes and computational power/tools, hence the app code can be short and transparent. The code (a single file) can then be distributed to students so they can run on their own laptops, thus in effect there is 24/7 access for all students simultaneously.

IV. Engaging and Interactive Resources Linked to Control

A core aim of the author is not only to create resources that are useful for their own students, but also resources that can be shared globally [18] and will be useful to international colleagues.

A. Vision for the toolbox

With MATLAB there are a large number of specialist toolboxes to support core topics, such as control, identification, optimisation, mechatronics and so forth. These can be added into the local version of MATLAB on a laptop using the *add-ons* button. The intention is to create a new "free" toolbox (https://controleducation.sites.sheffield.ac.uk/matlabresources/community-control-toolbox) which will be available through that route, and thus users would not need to know about a website address. There are also internal discussions about having some of the resources available through an institution webserver for users without personal access to MATLAB.

The initial focus is resources to support the teaching of "Control Systems 101" type courses and in particular interactive and animated resources which are largely self-explanatory, so easy to use. The intention is to use authentic scenarios across a broad range of topics which motivate the importance of control to modern society. These scenarios will be presented alongside some technical learning outcomes to support university curricula which users can engage with as appropriate. Resources are divided into:

1) Virtual laboratories with simple interfaces so students can select buttons and sliders to observe the behaviour of authentic scenarios and see how different parameter choices affect behaviour. Many of these could also be useful to users who are not studying at university.
2) Livescript files which focus more on useful MATLAB code and technical learning outcomes so of use primarily to university students.

The intention here is to provide a pair of files for each laboratory. The first file is an app and focuses on animation and allowing the user to experiment quickly with behaviours and the impact of different parameters and disturbances on those behaviours. The second file is more like a manual (provided as a livescript file) giving some of the technical engineering background and analysis alongside some source MATLAB coding so that users can take greater control of the design and analysis aspects should they so wish. The two are clearly paired through a sensible naming convention.

The remainder of this paper will give a few illustrations of progress to date. These are simple enginering examples that most people can relate to include: i) the speed of a car; ii) tanks with desired levels; and iii) mixing tanks. In the long term we hope to gain a breadth of high quality contributions from a range of persons across the globe.

B. Cruise control

While not widely use in Europe due to the density of traffic and windy roads, in other parts of the world with sparser populations and long straight roads, cruise control is used frequently. Hence, given speed is an easy concept for most users to relate to, this is a nice engineering example of control in action. The underlying model can be constructed as having 3 inputs:

1) Throttle or accelerator pedal controls the power delivery; in effect treated as traction force on the road.
2) The slope of the road is a disturbance input.
3) The headwind is also a disturbance input.

Consequently, this provides an interesting example as the user can experiment with simple PI (proportional and integral) control laws, both for the certain case and also consider the impact of disturbances on the efficacy of the control.

The app (Figure 4) allows the user to change just a few parameters in order to keep the interface simple: i) car mass; ii) friction; iii) proportional and iv) integral. Also the user can select the environment conditions such as road slope and wind.

An overlay facility is embedded so that user can make systematic investigations and see how behaviour changes with parameter/disturbance changes. The legend (bottom right) keeps track of the user choices to aid clarity. Animations can be switched on to give some realism to the app, or switched off to reduce simulation time.

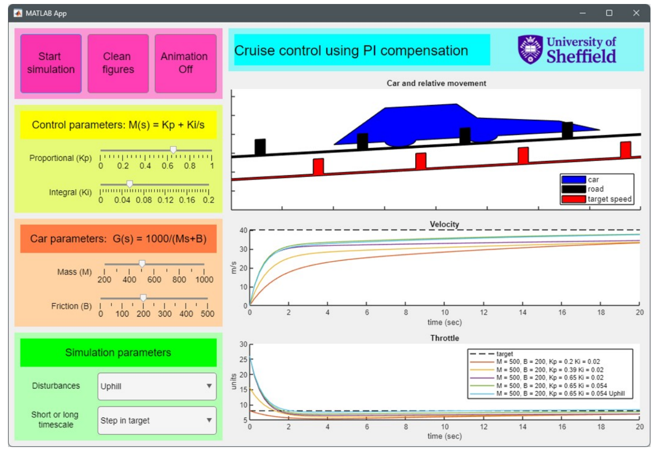

Fig. 4. Cruise control app interface.

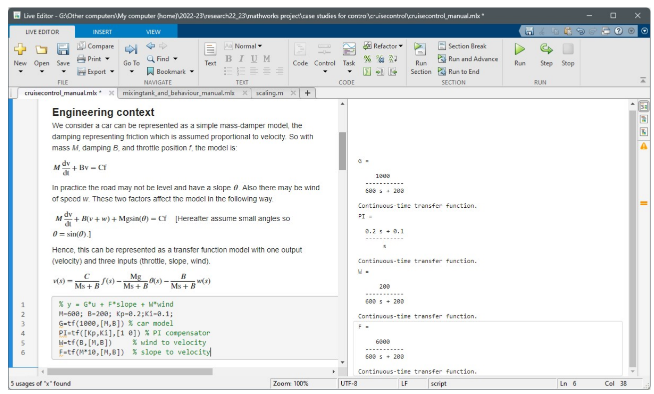

Fig. 5. Segment of livescript manual for cruise control.

Figure 5 illustrates a small part of the manual which is provided in a partner livescript file containing notes, equations and MATLAB code snippets for core analysis/simulation.

C. Mixing tank

A mixing tank is a common engineering element. In essence this is a large tank with an inflow and an outflow. Within the tank, stirring takes place to ensure even concentration. The aim is to achieve a desired outlet concentration by varying the inlet concentration. Some mixing tanks also host reactions so the outlet flow need not match the chemical make up of the inlet flow.

The app interface of Figure 6 has a number of sliders to capture the core system parameters such as tank volume, flow rate and initial conditions. Disturbances and input changes include inlet concentration, reaction rate and disturbance flows. The user can investigate the impact of changing these parameters while the animation uses colours and tank/pipe sizes to help with visualisation of the scenario. The app will store and display line plots associated to previous choices to allow easy comparison.

As with the other examples a manual file written as a livescript is also available.

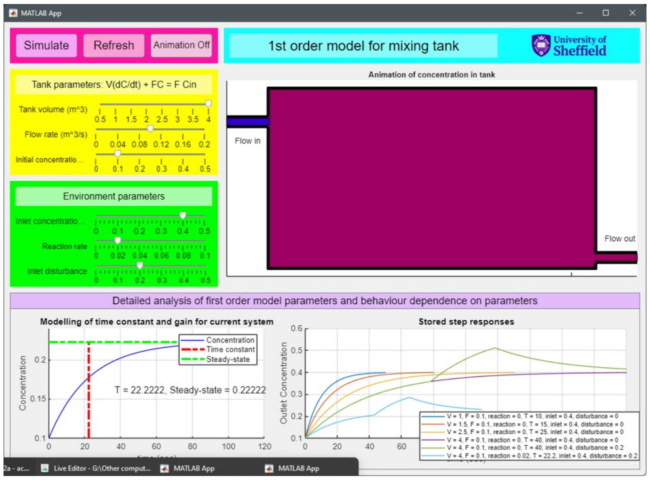

Fig. 6. Mixing tank app interface.

D. Tank level control and storylines

The two examples above focus on a single page interface with a limited set of learning outcomes such as open-loop behavior or PI design. There will be cases where it is convenient to have an entire storyline of how to tackle a control problem:

1) Open-loop behaviours and how these depend on the different parameters and disturbances.
2) Open-loop modelling or capturing the behaviour from data using a differential equation model.
3) Manual control of behaviour so the user can explore the limitations and challenges of human control approaches.
4) Automation, that is introducing computer based feedback control laws, removing the human in the loop.

The user will move through the tabs as their understanding develops and they progress through a course.

This section uses a tank-level system to represent this scenario. For example Figure 7 shows the first tab which is open-loop behaviours and how these are impacted by system parameters and disturbances; as ever animations of the effects bring the scenario to life for the users. Figure 8 shows the 3rd tab which allows the user to attempt manual control of the level in the presence of unknown disturbances (blockages and changes in flow) - it will be clear from the figure that this is not easy.

E. Plans for future developments

So far work has focussed on fairly traditional scenarios such as tank level, mixing tanks, cruise control, heat exchangers, house temperature control and so forth. At the time of writing only a few scenarios have been created as there is a secondary objective of defining good practice in coding of these apps and determining some coding and presentation standards which will be useful for future developments. These cover range of issues such as:

1) How to disable interaction while an animation is running.

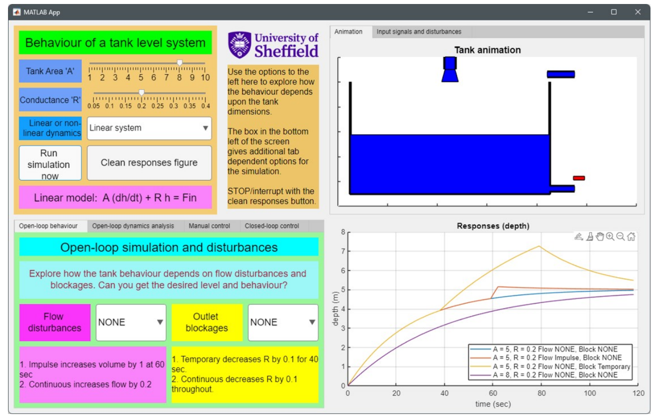

Fig. 7. Tank tank app interface on first tab (behaviour).

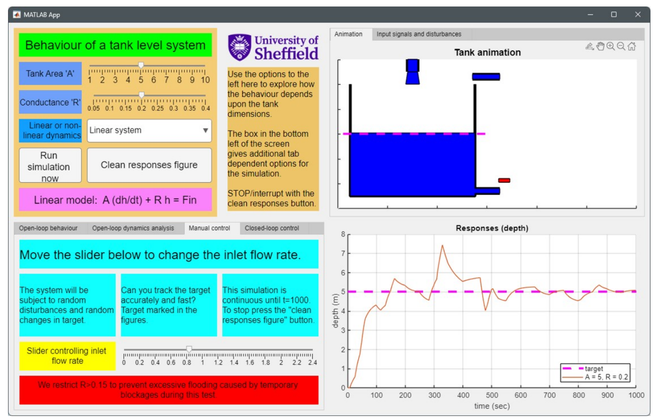

Fig. 8. Tank tank app interface on 3rd tab (manual control)

2) Allowing scaling for different screen sizes (requires grids) and consistent presentation.
3) Allowing the user to switch animations on and off to control the simulation time.
4) Correct structuring and selection of subfunctions and shareable internal variables.
5) Appropriate commenting and user help within the confines of the environment.

Ultimately the intention is to broaden the resources significantly to include scenarios such as agriculture and biosciences, finance, sociology and more. The underlying aim is twofold: firstly to show the relevance of control to a wide range of important problems and secondly to focus in more detail on specific control tools, algorithms and techniques that can be used and how to use them. The author and his department aim to have a sensible suite of files/apps packaged into a draft toolbox to demonstrate by July 2023 alongside a call for proposals and collaborators to help add to this.

In the short term files will be deposited in section 6.10 of the website [18] once suitable offline testing is complete.

V. CONCLUSIONS

This paper has introduced a project on producing a new MATLAB toolbox on control. The aim is to develop resources which enable users to engage with some societal challenges and understand what sort of factors effect the behaviours we can obtain, while protecting them from the equations and theory which underpin this? However, the resources will also allow users to engage with solutions at a level appropriate to a first course in control (and ultimately beyond this) and thus do cover technical detail and theory for those who wish to learn and understand this.

The paper has highlighted a few of the resources in preparation so readers can get some impression of the overall aims. A more complete set of draft resources will be available by July 2023 directly through MATLAB, and in the interim code free to download from a website [18]. At this point in the project, we are particularly keen on feedback from international colleagues so we can improve the resources and project vision. The author is also interested in potential collaborations to extend the breadth and depth of the resources available.

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