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MATLAB apps to support the learning and understanding of simple system dynamics

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Abstract: This paper focuses on resources which enable students to be active rather than passive in their learning. Important underpinning skills for control engineering is a good understanding of basic models and the associated dynamics. This paper presents a small number of MATLAB APPs designed to bring dynamics to life by allowing an interactive and visual element relating the behaviours to real components and system architectures. The paper presents the APPs, shows how they are integrated into course delivery and also gives some concise student feedback.

Keywords: Interaction within a lecture, virtual laboratories, independent learning.

1. INTRODUCTION

In recent years there has been substantial work on remote and virtual laboratories (Abdulwahed, 2010; Cameron, 2009; de la Torre et al., 2013; Dormido et al, 2012; Vargas et al., 2011; Fabregas et al., 2011; Goodwin et al., 2011) and significant evidence (Rossiter et al., 2018, 2008; Rossiter, 2017) therefore that these can be an effective part of course delivery. Alongside that, there has been a steady growth in the usage of so-called 'take home labs' (Hedengren, 2019; Rossiter et al., 2019; Taylor, Jones and Eastwood, 2013; Stark et al., 2013). Staff who were actively engaged in such developments probably had an advantage during the recent pandemic as they had ready made resources that could be deployed with students while access to more expensive university laboratories was difficult and limited at best.

This paper therefore takes the potential benefits of virtual laboratory and take home laboratory activities as well accepted in the community and asks: how can we add to this? This author in particular has an interest in what could be called quick and cheap solutions which do not require technical or other expertise (Rossiter , 2016; Rossiter, 2017). The point is that many academics have neither the skill nor time for professional solutions such as produced in Hedengren (2019); Cameron (2009). Moreover, their departments may not have the financial resource to provide such solutions to their students; even relative cheap take home laboratories at 30-40 USD per student quickly becomes a large bill with classes of 200+! Conversely, it is common for MATLAB or equivalent tools to be available free at the point of use by students in many universities and thus activities built around this software engine are cost free (in cash terms); clearly there are still the implied development costs which usually amount to staff time. They also have the advantage that every single student, no matter how large the class, can access these laboratories simultaneously and indeed, even during lectures!

The author has produced a number of MATLAB GUIs over the years (available on his website (Rossiter, 2021)) to support learning and understanding of introductory control concepts, but in recent years Mathworks has ceased support for the GUIDE environment and is instead promoting a new tool *MATLAB APPS*. Consequently, there is a need to adopt the new tool to ensure sustainabilty, maintenance and easy access for students.

A particular topic that the author has found students struggle with is 1st order responses and their characterisation. His perception is that students are trying to memorise every single engineering scenario he demonstrates rather than focussing on the unifying concepts underpinning them all; perhaps a hang over from the learning that was successful at school? Consequently, he is keen to encourage students to focus more on the concepts in their learning, and interactive tools allow them to experiment and ask intelligent but directed questions: *what happens to behaviour if a given component changes and what does this look like?*

In summary, this paper introduces a number of MATLAB APPs that have been developed recently. The intention is that these APPs can be used actively during lectures, not just in offline study by the students. The code is shared on section 6.8 of the author's website (Rossiter, 2021) so free for anyone to access and use.

The apps will be introduced in section 2 and then section 3 will give some discussion on their usage in teaching and student feedback on their efficacy. The paper then finishes with conclusions.

2. MATLAB APPS TO SUPPORT LEARNING OF 1ST ORDER BEHAVIOURS

This section first introduces the basic engineering and mathematical foundation before focussing on the detailed scenarios covered in the APPs.

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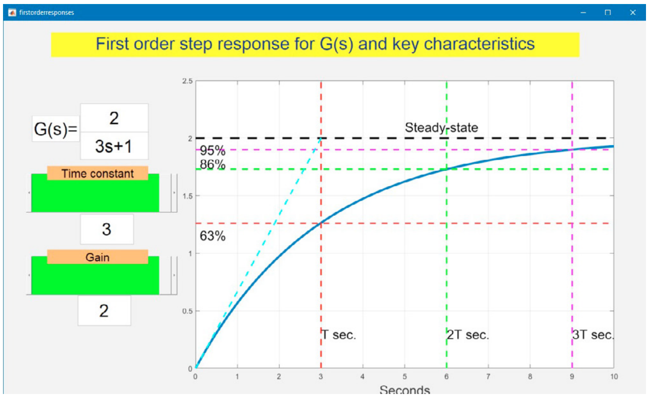

Fig. 1. Characterisation of a 1st order model step response (here with zero initial condition).

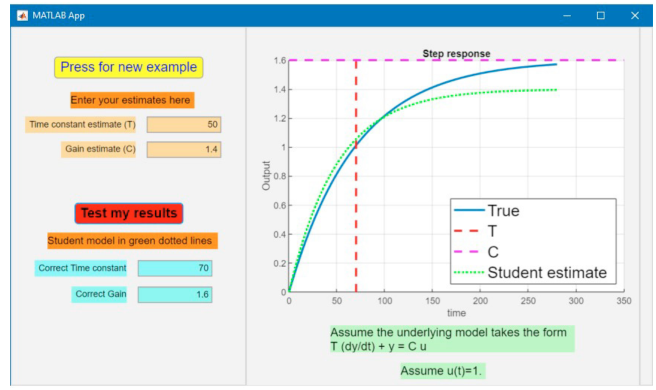

Fig. 2. Estimating time constant and gain from a step response.

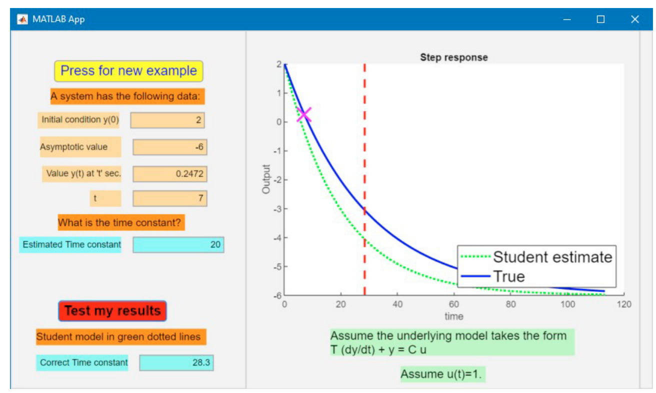

Fig. 3. Estimating time constant from limited step response data.

2.1 Basic concepts and mathematics

This paper takes the assumption that a 1st order model can be represented as:

$$A\frac{dx}{dt} + Bx = Cu \tag{1}$$

so with state x, input u and model parameters A, B, C. Generally the behaviour is easiest understood by representing in time constant form:

$$T\frac{dx}{dt} + x = Ku; \quad T = \frac{A}{B}, \quad K = \frac{C}{B} \tag{2}$$

where T is the time constant and K the steady-state gain. The solution, for a constant input $u(t) = \beta$, is given as:

$$x(t) = (x(0) - K\beta)e^{-\frac{t}{T}} + K\beta \tag{3}$$

This can be characterised using vertical lines at times $T, 2T, 3T$ and horizontal lines to represent 63%, 86% and 95% movement, as seen in Figure 1.

Hence, a core aim is for students to appreciate the essential invariance illustrated in Figure 1 and how the model parameters (e.g. A, B, C in (1)) thus impact on the behaviour and implicitly, how this applies to a wide range of engineering scenarios. A good understanding of the underpinning mathematics and behaviour means that students can easily translate this to a large number of different engineering disciplines, as required, and as shown in the following examples.

2.2 Supporting learning of basic concepts and mathematics

The most basic skill is to identify time constant and gain from a step response. An earlier GUI (see Figure 1) allows the lecturer/students to modify time constant and gain and view this invariance through the intersection of vertical lines at $T, 2T, 3T$ and horizontal lines at 63%,86% and 95%.

The first new APP shown in Figure 2 produces random step responses (use button *press for new example* to get a new example) and then asks student to enter in the orange boxes their estimates for time constant and gain. When the USER presses *test my results*, the APP does an overlay of their model with the original model so the user can evaluate their correctness and understand where an error may have occured; the correct time constant and gain are displayed both numerically (in blue boxes) and by lines added to the figure (both only added after *test my results* is selected).

A second APP (Figure 3) is quite similar, but focuses a little more on the mathematical equation of (3) and asks: can you still estimate the time constant if the data you have is not placed at precisely $t = T$ but rather some other time, marked in the figure by the pink cross? In essence it is focussed on the observation that the movement is given by:

$$K\beta - x(t) = (K\beta - x(0))e^{-\frac{t}{T}}; \tag{4}$$

The time constant can be estimated from (4), assuming the other values are known. Again, students enter their estimate and an overlay of their estimate with the true response is provided.

2.3 Tank level behaviour

Tanks are common in industry and an ideal simple example for dynamics and control. A common scenario is to assume an inflow which is the control input and an outflow which is proportional to depth (approximately in reality). This leads to a simplified model of the form:

$$F_{in} = A\frac{dh}{dt} + Rh \tag{5}$$

where A is the cross-sectional area, Rh is the out flow (for some constant R) and F_{in} is the in flow. Interesting concepts for the student to explore are:

- What is the impact on behaviour of changing the cross-sectional area?

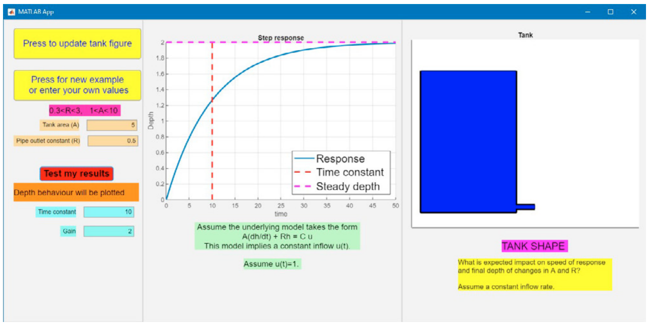

Fig. 4. Exploring dependence of level behaviour on tank area and outlet resistance.

- What is the impact on behaviour of changing the outlet conductance R?

Behaviour would be characterised by steady-state depth and speed of response/settling time or equivalently time constant.

Figure 4 shows the APP where students can try these things. The tank picture (press update picture) gives an impression of the tank area (wide or narrow) and similarly of the outlet conductance (large or small) to help students visualise the changes that are being made. Students can make manual selections in the brown boxes or generate random examples. The red *test my results* button updates the step response plot and adds lines for time constant and gain; numerical values are also displayed in the blue boxes.

Hence students can estimate, validate and visualise the impact of simple parameter changes on behaviour.

2.4 House temperature and heating

Maintaining the temperature in a house at a comfortable level is something we can all relate to, and thus is a good example to use. Clearly analogous systems are throughout industry. Again, in keeping with an introductory course, elementary dynamics are assumed so that heat loss is proportional to temperature difference with the outside and heat stored is proportional to temperature. Taking deviation variables for temperature θ as a given for simplicity, the model is:

$$W = C\frac{d\theta}{dt} + k\theta \tag{6}$$

where W is the power/heat suply, C is the specific heat of the house and k is the heat loss coefficient. Interesting concepts for the student to explore are:

- What is the impact on behaviour of changing the heat capacity?
- What is the impact on behaviour of changing the insulation (heat loss coefficient)?

Behaviour would be characterised by steady-state temperature and speed of response/settling time/time constant.

The APP (see figure 5) contains a simple visualisation of the house to help students relate to changes in C (large/small house) and changes in k (thick/thin walls). As earlier, along with the step response plots, the APP will update time constant and gain computations so students can assess their understanding of those two concepts and again: estimate, validate and visualise the impact of simple parameter changes on behaviour.

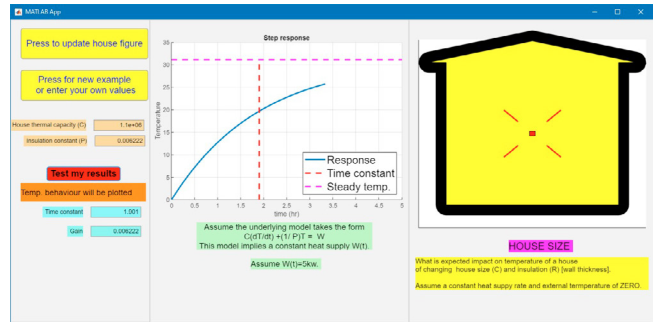

Fig. 5. Exploring dependence temperature behaviour on house size and wall thickness.

2.5 Car velocity

The velocity of a car is a simple example that most students can relate to quite well and thus have an intuitive understanding and expectation for the associated behaviour and its dependence on mass and friction. In this APP (Figure 6), students can change the car mass and road/air friction and overlay the step response behaviour, thus it enables them to see systematic trends such as for example, what happens as friction gets larger? A simple mass-damper model is assumed, that is:

$$f = M\frac{dv}{dt} + Bv \tag{7}$$

where f is the force on the road (assumed constant), M is the mass and B is the friction constant. Interesting concepts for the student to explore are:

- What is the impact on behaviour of changing the mass?
- What is the impact on behaviour of changing the friction?

Behaviour would be characterised by steady-state velocity and speed of response/settling time/time constant. The APP also displays the time constant and system steady-state gain for the current parameter choices.

A particular attribute of this APP is that it allows the user to overlay multiple different plots and thus plan and observe trends. Users can control the variation of the parameters by entering choices in the orange boxes rather than selecting *new example*.

2.6 Mass-spring-damper system

The final example shown in this paper introduces second order behaviours and under-damping using the classic example of a mass-spring-damper. Students can change the parameter values and the APP returns a step response and the current damping ratio, gain and effective time constant. As with the earlier APPs, the picture changes to reflect the parameter selections, for example a larger rectangle for a larger mass, thicker lines for a stiffer spring, etc.

Interesting concepts for the student to explore are:

- What is the impact on behaviour of changing the mass?

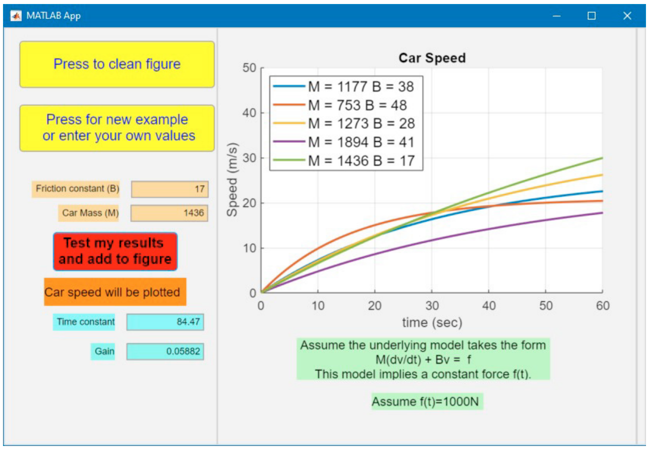

Fig. 6. Exploring dependence of car velocity behaviour on mass and friction.

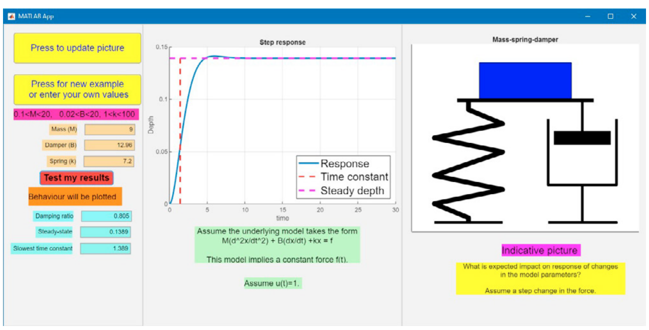

Fig. 7. Exploring impact of mass, spring and damper sizes on behaviour.

- What is the impact on behaviour of changing the friction?
- What is the impact on behaviour of changing the damper?

It should be noted that 2nd order systems and behaviours is an obvious area where more apps and insights could be developed.

3. ADOPTION IN TEACHING AND EVALUATION/REFLECTIONS

The APPs were designed with twofold purposes:

(1) For the lecturer to use during lectures.
(2) For students to use to support their independent learning.

3.1 Use by staff and in lectures

To some extent, the slightly cartoon nature of the animations can raise a laugh and promote student engagement where the lecturer is demonstrating these from the front. Critically however, the pictures are important for students to relate the changes in dynamics to the changes in parameter sizes and one can easily form exaggerated pictures (tiny house with very thick walls, very thin tank with very fat exit pipe, etc.) to emphasis the behaviours are exactly what students should expect.

Following a quick demonstration, students are then asked to run the APPs on their own laptops. It is common for nearly every student to have a laptop with them which is normally on, thus reminding them to open MATLAB and download the requisite files is easy. Students without a laptop can work with those sitting nearby. The author's observations are that, giving students a targeted time and encouragement to do this in lectures is rewarded by a substantial number engaging very actively. A secondary benefit is that students are more confident to run the APPs again in their private study. Indeed the author has seem several students using these during *drop in tutorial* slots and asking questions of the demonstrators.

The author has not yet integrated the use of the APPs into formal assessment as there was insufficient time this year and he also wanted a less high pressured dry run. However, he is considering doing this in the future as this is a good way of encouraging active and reflective engagement. Computer aided assessment quizzes are a natural and straightforward format to do this which he has adopted in the past.

3.2 Student evaluation

The introduction of the APPs was fairly light touch this year, and thus the evaluation was correspondingly light touch. Students were asked during lectures, 2 weeks after the APPS were introduced and recommended, for their impressions of the APPs and their efficacy in supporting the growth of understanding of core concepts. It should be emphasised that, as is probably commonplace, there will always be sizeable minority who are either not keeping up or have not quite got around to doing something yet. Hence 30-40% not being positive is almost inevitable; indeed this number may select neutral simply because, as yet, they have no opinion.

The questions asked were as follows.

(1) Did the APPs (tank, car, house) help you understand the concepts of 1st order behaviours (time constant and gain) and their dependence on real parameters?
    Around 70% responded positively, with the remainder being neutral.
(2) Did you use the APPs to validate you expectation of behaviour changes when given parameters were changed?
    The interesting thing here is the large number (circa 50%) who said they were planning to use the APPs in the future, but had not begun yet. About 50% had used them actively with most of those finding them useful.
(3) Did you find the APPs based on the mathematics (Figures 2,3) helpful for testing your numerical competency?
    This one had more mixed responses. While only a very small number did not like them, the summary was that those who used them found them useful, but many not had not engaged actively yet.
(4) Do you think including usage of the APPs in the quiz assessments would be useful for reinforcing your understanding of core concepts?
    This question had mixed responses as well. The younger cohort of students, who are perhaps less mature, felt that including usage in weekly quizzes would be a helpful encouragement to engage in a

timely fashion (only 16% disagreed and 23% neutral), whereas for the older cohort while the disagreed number was still small, far more students (45%) were neutral on this point.

Given the evaluation was mid-term the author feels it not only captures student views on the APP efficacy, but also gives some insight into student work patterns. It seems clear that students who used the APPs did find them a useful learning aid, but as perhaps is common, many students did not engage with optional activities to enhance their understanding and learning. Indeed, it is likely that encouraging students to use their laptops and MATLAB during lectures significantly increased usage compared to what would have occured without this lecture activity. The lecturer did however notice many students using the APPs during weekly drop in tutorials.

4. CONCLUSIONS

This paper has presented a number of MATLAB APPs that can be used to support teaching of introductory dynamics as part of a first controls course (Rossiter et al., 2020). It is important that students have an appreciation of what dynamics mean and how these relate to real systems, so where access to laboratory hardware is limited, the APPs allow simple but effective visualisation of core concepts. Moreover, being MATLAB based, they allow the entire class to access simultaneously and moreover, runtimes are essentially instantaneous.

The author has used these during lectures and critically, as students nearly all carry laptops, encouraged students to also run these during the interactive slots within the lectures thus moving them from being passive to active participants. His personal impressions were that a lot of students were using the APPs both during and outside lectures, thus gaining the associated learning and experience.

A light touch student evaluation reinforces the lecturer perception. Those students who used the APPs in the private study (or indeed during the lectures) found them useful, but a significant minority had not yet engaged with them and were planning this for some future, unspecified, time. In general there was a recognition that compelling students to engage with the APPs by incorporating into weekly quizzes would probably be beneficial to learning and thus this is something the author will consider for future years.

In terms of future developments, obviously a reliance on MATLAB is a potential weakness in terms of wider usage but coding in a more open source and perhaps mobile friendly language is non-simple and far more expensive. Similarly, there are clearly many possible scenarios and behaviours that could be explored more by either embellishing the existing apps, or creating new ones.

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