From Theory to Hardware: Control of a "Balance Bot"

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***Abstract*—We present a proposal for a 3-hour tutorial to be held at ICC 2025. The authors represent the e-Yantra project, whose stated mission is to impart hands-on skills to students in the areas of robotics and embedded systems. The goal of the proposed tutorial is the same: to encourage and enable attendees (especially students) to translate concepts from control theory and machine learning into actual deployments in hardware. The tutorial shall complement the traditional focus of ICC on methodological advances by exposing attendees to tools and techniques on the applied side.**

In this document, we provide background on e-Yantra, then switch to a technical description of "e-Yan", a 2-wheeled "balance bot" designed by e-Yantra. The technical portion of the tutorial will take participants through a series of steps (first in simulation, then on hardware) to control the balance and navigation of e-Yan. Methods implemented will include PID, LQR, and reinforcement learning (RL). The document specifies a detailed administrative plan, and follows by listing the expected outcomes of the tutorial.

I. e-Yantra Initiative

The Indian education system plays a direct role in determining the future of tens of crores of young individuals, thereby making a fundamental and significant contribution to economic growth and well-being. A noticeable shortcoming of the educational setup is its deficit in imparting "hands-on", practical skills to students [3]. e-Yantra was founded in 2009–10 under the National Mission on Education through Information and Communication Technology (NMEICT), and has thereafter been run as a project out of IIT Bombay. The core philosophy of e-Yantra is "project-based learning", which challenges students with real-world problems and encourages them to "learn by doing". The technical focus areas have been robotics and embedded systems, covering topics such as control systems, UAVs, FPGAs, and multi-agent coordination. With a resident staff of 20–30 at any point of time, e-Yantra manages an ecosystem of interconnected activities, including lab setups in colleges, a popular robotics competition, innovation challenges, workshops, internships, MOOCs, and so on. For more details the reader is referred to the e-Yantra web page [5].

In the last 15 years, e-Yantra has set up over 550 labs across the length and breadth of the country (see Fig. 1). These labs are equipped with hardware and software resources, and receive continuous mentoring from the e-Yantra team. In the process, over 200,000 students have been trained using an exciting mix of themes and challenges, a small sample of which are shown pictorially in Fig. 2. e-Yantra training has routinely improved employment prospects [2]. Several e-Yantra alumni have gone on to build successful start-ups in the areas of robotics and automation [6].

Central to e-Yantra's success at scaling up has been its well-understood process of learning by doing, segregated into separate topics and workflows (called "themes"). Control systems has been among e-Yantra's themes for over a decade now; the robots shown in Fig. 2a and Fig. 2b have been used to train students to apply off-the-shelf control algorithms such as PID and LQR. While the focus of e-Yantra has primarily been on educational outreach and applications, the traditional focus of ICC has been complementary: towards advancing research and development in the area of control systems.

The authors, who represent e-Yantra, propose to conduct a tutorial at ICC 2025 with the broader goal of realising the synergy between e-Yantra and ICC. In particular, they believe that the student population interested in control theory may benefit from quick, yet intensive, exposure to the applied side of control. Shortages of labour and skill in areas such as agriculture and manufacturing are now well-documented [7] [11], implying that economic growth will critically depend on automation in these areas. It is hoped that the tutorial will encourage young students to think seriously

(a) (b)

Fig. 1: (a) Locations of e-Yantra labs, as of September 16, 2025. (b) Participants interact with judges during the finale of the 2025 e-Yantra Robotics Competition, held at IIT Bombay. Pictures courtesy e-Yantra.

(a) (b) (c) (d)

Fig. 2: Representative robots designed and operated by e-Yantra staff and students. (a) 2-wheeled "balance bot" similar to e-Yan (see Section II). (b) Small-size drone. (c) Multi-link "snake". (d) Water surface-skimmer. Pictures courtesy e-Yantra.

about contributing to applied research and development.

e-Yantra is a non-commercial entity, funded entirely by the Ministry of Education, and fully aligned with the commitment of IIT Bombay to educational outreach. The tutorial will not promote any private or commercial interests.

In the upcoming section, we describe "e-Yan", a "balance bot" designed and developed by e-Yantra, which will anchor the proposed tutorial.

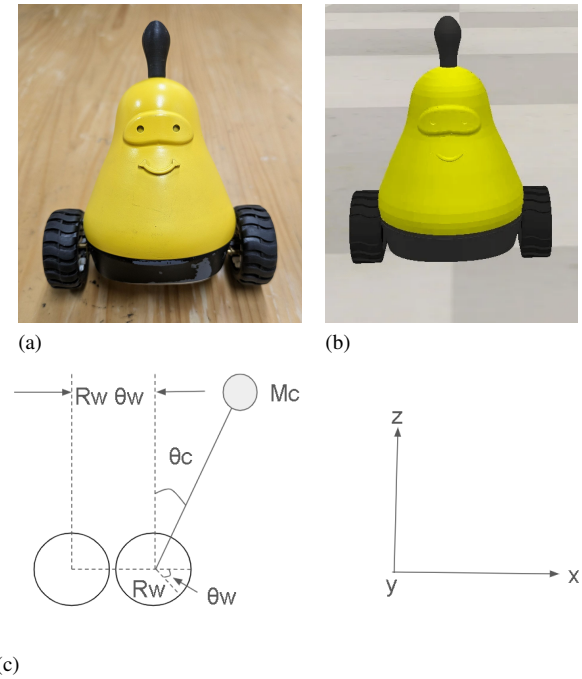
II. Balance Bot e-Yan

e-Yan, shown in Fig 3a, is a 2-wheeled robot with dimensions of $8.5cm \times 11.5cm \times 13.8cm$, weighing approximately 228 g. By applying torques of the same magnitude to the wheels (suitably directed), the robot functions as an inverted pendulum in a single dimension. Differential controls to the wheels can also induce rotation about a vertical axis.

The mechanical design as well as the control circuitry of e-Yan is completely done by the e-Yantra team. The wheels are controlled by N20 gear motors (250 RPM with encoders), to which commands are sent from a Xiao ESP32C3 microcontroller. Mounted on a custom-built PCB, e-Yan is fitted with an MPU6050 IMU sensor, which, along with the encoders on its motors, provides state information. The microcontroller can be programmed using Arduino IDE [1]. The same code integrates seamlessly with a high-fidelity simulation using the CoppeliaSim framework [9] (see Fig. 3b). The e-Yantra team has also developed a navigation app to provide high-level commands to the e-Yan through a phone.

For simplicity assume that the e-Yan is controlled as a single-dimensional inverted pendulum, with the sole aim being balance. In this case, the state may be abstractly viewed as a 4-dimensional vector that encodes position x, velocity $\dot{x}$, angle θ, and angular velocity $\dot{\theta}$. The control is a single signal in $[-1, 1]$, specifying the torque magnitude and direction to apply to the wheels. The system indeed behaves like an inverted pendulum, as depicted schematically in Fig. 3c. Since system parameters are known with relatively high accuracy, e-Yan can be controlled effectively with LQR control [4, Chapter 8], as also with alternatives such as PID [8, Chapter 8] and reinforcement learning [10].

For 2-dimensional navigation, only minor modifications are required to the controllers developed for the 1-dimensional inverted pendulum setup. The e-Yantra team has successfully implemented several variants of PID and LQR on e-Yan (both in simulation and in hardware). The purpose of the tutorial will be to facilitate participants to do the same. In addition, we expect to tutor students on the use of value-based RL (in particular, the Sarsa learning algorithm) in simulation (the time constraint might prevent training and iteration in hardware).



(a) (b) (c)

Fig. 3: (a) Front view of e-Yan robot. (b) e-Yan in a simulation environment. (c) Free-body diagram, side view. Pictures courtesy e-Yantra.

III. Tutorial: Administrative Details

In this section, we cover aspects related to the organisation of the tutorial.

A. Overall scope

The scope of the tutorial is two-fold: first to sensitise participants to the relevance and utility of hand-on skills, and second to give them the experience of building applications in hardware. Consistent with these goals, the introductory and concluding portions of the tutorial will focus on the big picture around "learning by building", while also outlining problem statements from the Indian ecosystem. The e-Yantra team has gathered numerous problem statements from agriculture and manufacturing; these will be presented for the benefit of the attendees. The core aspect of the proposal (roughly 80% of the allotted time) will be technical, beginning with an introduction to e-Yan, followed by quick introductions to PID, LQR and reinforcement learning (RL) for control. While covering these topics, participants will simultaneously be writing and evaluating code in simulation and in hardware.

B. Programme

A systematic break-up of the allotted 3 hours into a sequence of modules is provided in Table I. Modules 3, 4, 5, and 6 will involve live demonstrations by the instructor, with the participants coding and experimenting (both in simulation and in hardware) in parallel.

C. Resources

All the software to be used for this tutorial is free and open source. Participants will be expected to bring their own laptops pre-loaded with the relevant software (which will be specified to them ahead of time). Thus, all the simulation work will be carried out in the partcipants' own laptops. The e-Yantra team will bring approximately 30 hardware models of e-Yan, which will be provided to the participants for hardware testing.

D. Registration counts and structure

Depending on the number of registrants, teams may have to be formed. Teams of size up to 3 are typical at e-Yantra workshops, and are even considered ideal. The organisers are open to the idea of conducting some part of the tutorial as a "competition", with the top few entries being ranked and felicitated. A group of size 40 can be handled without any additional personnel for training. In case registration counts are larger, it might be necessary to bring additional e-Yantra staff for assistance. The authors shall consult the conference organisers with regard to such logistical issues once registration counts become known.

E. Organisers

Brief biographical details of the authors, who are also the organisers, are included below.

- **Shivaram Kalyanakrishnan** (corresponding author) is Associate Professor in the Department of Computer Science an Engineering at IIT Bombay. He is Principal Investigator, e-Yantra. His research on intelligent and learning agents covers both theoretical topics (such as multi-armed bandits and MDPs) and applications (including railway scheduling, imperfect-information games, robot soccer, and finance). He teaches an elective course on these topics at IIT Bombay, which attracts a registration of 200–300 in each offering.

- **Kavi Arya** superannuated in June 2025 from the position of Professor in the Department of Computer Science and Engineering at IIT Bombay. His research contributions are in the areas of functional programming, embedded systems, and education technology. He founded e-Yantra, and was Principal Investigator 2010–25. Kavi Arya has spent several years in industry (IBM Research, Tata Research DDC, Mahindra & Mahindra), and is on the advisory committees of several national agencies (such as CDAC, NABARD, Indian Army, and Mumbai First).

TABLE I: Programme and timetable.

S. No.	Module	Presenter	Duration (minutes)
1	Welcome and introduction	Shivaram Kalyanakrishnan	5
2	Introduction to learning by building	Kavi Arya	15
3	Balance bot e-Yan: hardware and software	Jerish Abijith Singh A. S.	35
4	PID control: theory and application	Jaison Jose	35
Break			
5	LQR control: theory and application	Arun P. Madhu	35
6	Reinforcement learning: theory and application	Shivaram Kalyanakrishnan	40
7	Recap; opportunities in applications of control	Shivaram Kalyanakrishnan	15

- **Jaison Jose** is a Senior Project Technical Assistant at e-Yantra, and is currently pursuing a masters degree in the Department of Electrical Engineering, IIT Bombay. He has conducted 7 workshops on embedded systems and control systems in colleges across the country, and is a theme leader in the e-Yantra Robotics Competition.

- **Arun P. Madhu** is a Senior Project Technical Assistant at e-Yantra, and is currently pursuing a masters degree in the Centre for Systems & Control, IIT Bombay. He has conducted 4 workshops on embedded systems in colleges across the country, and leads the drone theme at e-Yantra.

- **Jerish Abijith Singh A. S.** is a Senior Project Technical Assistant at e-Yantra, and is currently pursuing a masters degree in the Department of Electrical Engineering, IIT Bombay. He has conducted 4 workshops on embedded systems and control systems in colleges across the country, and leads the control systems theme at e-Yantra.

IV. Expected Outcomes

The tutorial will familiarise participants with software tools such as CoppliaSim and Arduino IDE, which allow for rapid prototyping of control algorithms in a realistic setup. Moreover, access to the actual hardware version of e-Yan will sensitise participants to the hardware/software interface for programming control algorithms. Practical issues such as noise and lags will become apparent in the process.

At a deeper level, we believe the experience provided by this tutorial will spur more researchers to work on the applied side of control. Reinforced with actual problem statements that we provide from areas such as agriculture and manufacturing, we hope that many young students will consider career paths to contribute to these areas. For those interested, the e-Yantra team will be happy to facilitate direct contact with partners such as agricultural universities.

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