MOTORS + MOTOR CONTROL LEARNING MAP

MITMECHE

WHY DID WE BUILD THIS MAP?

As a group, we've also been looking a lot into the science of learning. That is how we learn, and how we can teach so students can learn better. A lot of this comes from **applying psychologial research to engineering education** which is actually **less common than you might think**. One of our takeaways from this was **sometimes teachers struggle to understand which concepts students are struggling with** because as *we achieved mastery* of a subject, our brain *forgets where we were while learning those very concepts*. Our brains fill in previous memories assuming we knew information we now know today, even if we did not. This is a **Metacognitive Error** commonly called, "the Curse of Knowledge" or the "Knew-it-all-along" effect.

Therefor we slowly, and carefully built this map so we could remember how we got where we are, and so you can understand why we are teaching things in a certain order or in a specific way.

GREAT BOOK. WOULD RECCOMEND TO ANY EDUCATOR OR STUDENT

IDENTIFY WHERE YOU ARE ON THIS LEARNING MAP, THAT WILL BETTER AID YOUR LEARNING. WE PROMISE!

ANY YOU DON'T NEED TO LEARN EVERYTHING ON THIS MAP ALL AT ONCE. IT TOOK US YEARS, BUT IT'S HERE TO GIVE YOU AN IDEA OF WHERE YOU ARE, COMPARED TO WHERE YOU WANT TO GET!

IT LOOKS LIKE A LOT, BUT DON'T LET THAT DETER YOU! THE MOST POWERFUL LESSON IN LEARNING IS KNOWING WHAT YOU DON'T KNOW!

NOTE THAT THERE'S EVEN MORE TO LEARN THAN JUST THIS, WE NEVER STOP LEARNING AND THE KEY IS CONTINUED PRACTICE IN THESE AREAS TO BECOME A MASTER.

Basic Understanding of Electrical Circuitry, Voltage + Current + Etc

Somewhere here you take intro physics E&M

Some Wiring Knowledge

Start

Motor Hooked up to a Power Supply, Vary Voltage, Notice Speed Changes

Motor Stall Tests, Vary Current, Notice Torque Changes

Play with an RC car or plane and notice main components of a motor + control system

Milestone 0: Experimental Understanding of Motors

Learning Milestone

Decision

You Decide to Experiment More

Somewhere here you join a robotics team, or decide to build an electric sooter, RC car, or drone

(note that this part involves a lot of experimenting, playing, and innate curiosity.)

Somewhere along here you melt through a wire and learn Wire Gauge Matters

Somewhere along here you learn violating voltage and current limits in devices cause them to explode

Somewhere here you get a preliminary understanding of batteries

You learn that motors have a torque limit and a speed limit

You learn about the concept of 'Kv' but it doesn't really make sense

You learn motor controllers can help you control motors to do what you want

Somewhere here you learn about arduino programming, servos, PWM, and sending signals to motor controllers

You go to online R/C forms or robotics forms and read about how people pick motors and motor controllers for different applications

(HERE IS WHERE MOTORS.MIT.EDU PICKS UP ROUGHLY)

You start to learn more about motors specifically

You Decide to Learn More

Decision

Learning Milestone

Milestone 1: Hobby-Grade Knowledge

(note that here some people have discovered brushless motors as well, but it's important to understand brushed before moving to brushless)

Somewhere around here you notice you aren't getting the peformance you expect, like the motor you thought was strong enough, isn't really.

You think of more complex projects to do

You start building more projects and by now you can pick a motor and a motor controller, and put it in a system and it'll run with R/C control or simple arduino code.

(but you don't necessarily know what your torque or speed limits are)

(6.002 @ MIT and 18.03 @ MIT)

Somewhere here you take a more advanced circuits class

Somewhere along here you learn Differential Equations

You learn about peak power point, and power curves

You learn about torque-speed cruves of brushed motors, you can now explain the limits of a small motor

You learn about BackEMF and the electrical circuit model of a motor

You do some more experiments and you can apply that knowledge to hardware, you can select motors for an application (given a motor controller)

You learn about the basic model of "commutation" in a brushed motor, and you learn WHY its called a brushed motor

Somewhere here you take an intro Mechatronics class

Decision

You Decide to Learn More

Learning Milestone

Milestone 2: Familiarity with Brushed Systems

(where students are at the end of 2.007 @ MIT)

Somewhere here you learn about circuit elements, microcontrollers, transistors, and other power devices

(Familiarity not mastery)

You learn about PWM for power, and H-bridges, and how brushed motor controllers work

(where students are at the end of 2.678 @ MIT)

Somewhere here you take an intro controls class

(something like 2.004)

You learn about closed loop control, current sensors, voltage sensors

You implement PID speed and position control

You get exposed to more interesting control concepts such as "torque control" as opposed to "voltage control" and become curious

Somewhere here you take a power electronics class

Somewhere here you learn about PCB design

You look more into robotics and learn about torque control

(something like 6.131 @ MIT)

You try to design your own brushed motor controller

You implement torque control on a DC motor and observe some characteristics

If you're really advanced you look into impedance control and other advanced topics in motor control, you make a jumping robot leg

(where students are at the end of 2.74 @ MIT)

You take a more advanced mechatronics class

Somewhere here you learn about ADCs, PWM timers, memory, and other microcontroller details

(something like 6.115 @ MIT)

You learn about using a brushed motor as a generator and play with that a little

You can now pick sensors, design brushed motor controllers, pick a brushed motor, and implement it in a lot of projects

Milestone 3: Mastery of Brushed Systems

Learning Milestone

Decision

You discover the brushless motor there's no turning back now...

Continued Below

Continued Here

You start playing with brushless motors and wonder why there are three wires

You identify differences between brushed and brushless motors, your learn about the star node, coils, and magnetism

You learn about the simple single-pole, three-coil model of a brushless motor and phases A, B, and C

You start googling electric commutation and you find six-pulse control. you play around with that for a little bit

You find the "3 sine waves offset by 120 degrees" but it's still hard to visualize what is happening

But you understand the frequency of the sine waves relates to the motor speed when there's no load

(you kinda get here in 6.131)

You notice your control isn't great and your motors aren't achieving the performance you want, or you start to wonder how to do torque control on brushless motors

You learn about Field Oriented Control (FOC) and start looking into it

You learn about Space Vector Modulation (SVM) and start looking into it

Somewhere here you look up open source motor controller projects, and their associated code.

You learn about the Clarke and Park transforms, start to piece together FOC with current and torque control

Somewhere here you notice your motor control isn't great AGAIN especially at low-speeds, and you realize some motors have encoders on them

Somewhere here you learn about the different types of encoders

You combine what you know from the brushed domain and now you can select brushless motors for applications, and select a controller

You learn about the relatioship between Kv, Kt, and backEMF

You learn more about brushless motor torque speed curves, you learn about the Kt of a motor, you learn about magnetic saturation

You learn about pole-pairs, winding resistance, flux linkage, and other motor parameters

You adjust what you know about power curves and peak-power-point to the brushless setting

You learn about matching motors to controllers using 'Power'

You learn how to measure Kv and Kt with an oscilloscope

Learning Milestone

Decision

You Decide to Learn More

You start looking at motor dynamometers

Somewhere here you learn about gap radius, lenght, field strenght, and its affect on torque density of a motor

You start learning about winding patterns, and the relationship between poles and slots

Milestone 8: Understanding of Motor Design

Learning Milestone

Decision

You Decide to Learn More

You start learning about magnetic materials and magnetic circuits

Somewhere here you take a more advanced E&M class

You look up different types of motors, you look at their structure

You discover other types of motors such as IPMs, and reluctance motors

You learn about efficiencies, core losses, switching losses, winding losses, and more

Somewhere here you learn about Ansys Motor CAD (or similar)

Somewhere here you play a little with magnetic viewing film

You learn about hallbach arrays, flat windings and other advanced techniques

You learn about bearing selection, loads on motors, and designing for mecahanical robustness

You learn about thermal models, and other electro-mechanical considerations

Milestone 9: Fluent in Aspects of Motor Design

(note that motor design can get very complex, Fluency is described as understanding motor design to the point where you can manipulate the appropriate parameters to design a motor, it does not necessarily mean optimization or mastery of the subject)

Milestone 4: Familiarity with Brushless Systems

Learning Milestone

You learn about regenerative braking and understand its interplay with FOC

You play with controllers already on the market, learn about motor control parameters, and learn how to setup motor controllers to get desired control behavior

Decision

Somewhere here you learn more about MATLAB/Simulink or other simulation tools for motors / motor control

Milestone 7: Simulation of Motors + Motor Control Systems

Somewhere here you learn about data sampling rates and the Nyquist Frequency

You learn about efficiency maps and power maps

You learn about active dynos, inertia dynos, eddy current bakes, testing procedures and more

You learn about stall tests, free-speed tests, peak-power tests, and how to build these maps

Milestone 6: Understanding of Motor Testing, and Power Generation

You reference other motor control projects and resources

You get more comfortable with the math behind motor control, state machines, and firmware

You discover gate driver chips, IGBTs, power MOSFETs and other goodies related to motor control

Somewhere here you learn about SPI, CAN, I2C and UART, and other communication protocols

Somewhere here you learn more about the detailed workings of transistors, selecting components

Somewhere here you learn about advanced circuit design, impedance, trace width and robust PCB design, signal processing

You begin to design your own inverter and write the firmware for it

You get an internship, research experience, take a class, or you work with a friend who knows a lot about motor control

You learn about calibration routines for FOC, and feed-forward compensation terms in FOC

You learn how to layout a microcontroller on a PCB

You learn about power loss, switching loss, and other detailed considerations required when designing drivers

You learn about current sensing, gate drives, and bus/bypass capacitance

(note that at the higher levels, we assume that enough learning is present so the student can determine what aspects of the field they need more or less knowledge in based on their own experiences)

Somewhere here you learn about electrical design for high voltage and high power systems, including isolation and thermal management

The PCB and firmware for your motor driver work

Maybe this needs a few revisions, you rely heavily on open-source code and resources

Somewhere here you learn about control bandwidth, how to tune a closed-loop current controller.

You learn about more advanced forms of control, PID loops, impedance control, Field Weakening, and more

You've learned how brushless motors work because you designed and implemeneted a controller

Milestone 5: Mastery of Brushless Control Systems

Learning Map Revision 1

Topic: Motors + Motor Control

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