Robotics 311 : How to build robots and make them move

Prof. Elliott Rouse

GSI Yves Nazon MS

Fall 2022

Photo credit: Brenda Ahearn / U-M CoE

ROB 311 – Lecture 19

- Review!
- This review is aimed to stitch the lectures together and provide greater understanding of the material

Announcements

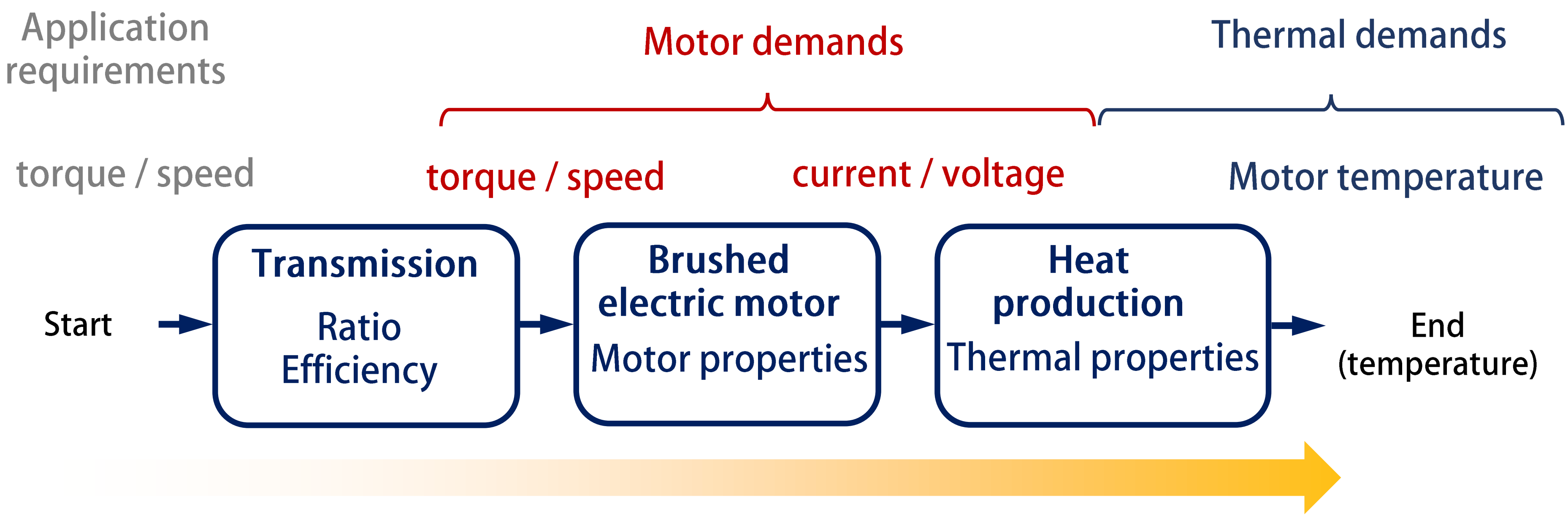
- T-shirts!
- Yves has posted all HW and quiz solutions—these are indicative of the types of questions we ask
- Midterm will be open note—we will provide the notes in a 2-slide format (would you prefer 4 slide?)
- It will consist of multiple choice and short answer problems
- It will cover up to Lecture 17
- You will be allowed / need a scientific calculator
- Bring your laptop—if we use it, you will need to turn off wifi
- Reminder there are *many* resources provided free on Canvas

What is involved in development of a robot?

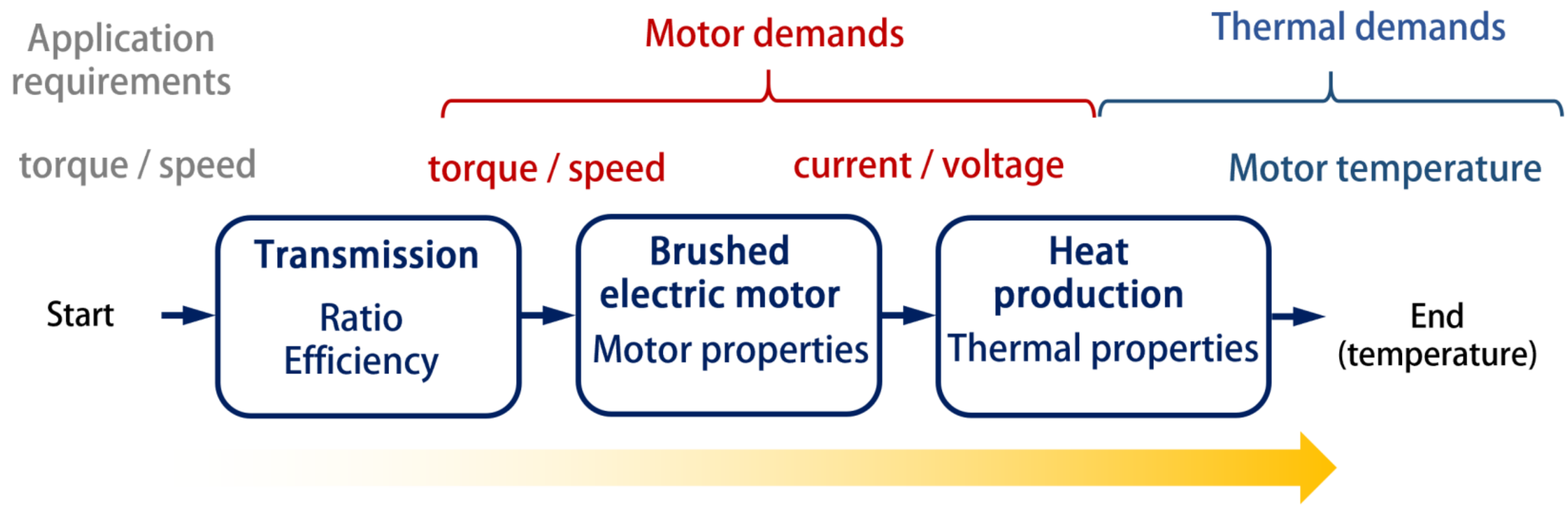
- The process begins with understanding the requirements
  - In this class, we focus on medium and low-level parts of robotics systems.
  - Meaning, higher level perception / AI-based control would sit above the subsystems described in this course
  - In the medium to low level, what does the robot have to do?
    - **Do a task** – but on a fundamental level (motion or force)
    - Examples: Track a position, force, torque, virtual spring-damper, etc.
    - Not examples: Open a drink, navigate a vehicle… Dexterous or complex tasks
    - How about for our ball bot? Roll the mass of the ball and fight any friction

Design Analysis Framework

- We learned a framework to understand the robot design process
- This framework will lead you to a viable design
- It consists of many steps to address the many requirements / attributes of robotic systems
  - Electromechanical / thermal modeling, design, manufacturing, sensing & communication, and control



Design Analysis Framework



What do we need?

- A description of the task
  - Torque-speed, force-displacement, etc.
  - Any electrical requirements (voltage, current limits, etc.)

What do we get?

- An analysis framework to investigate transmission ratios, power requirements, motors, and others...
- The framework enables the selection of a motor / ratio with the appropriate:
  - Torque, speed, current, voltage, and temperature

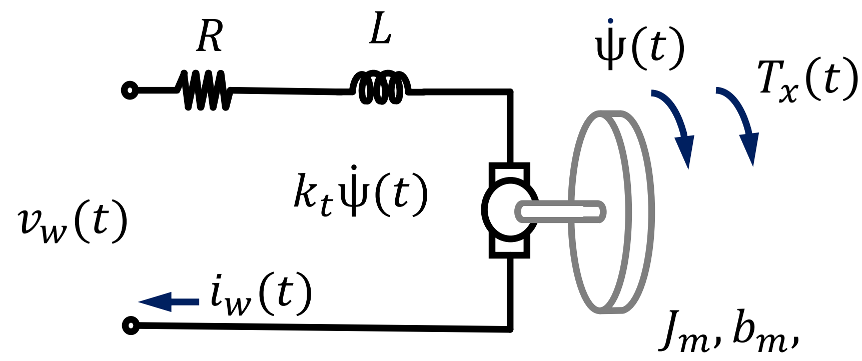
Modeling Brushed DC Motors

- How do you know which is right for your application?
- We quantify required torque / speed and current / voltage to make decision
- Typically assessed in tandem with the transmission ratio
- We discussed analyses that help you make this decision

Modeling Brushed DC Motors

For brushed dc motors: $k_t = k_b = \frac{1}{k_v}$

- Governing equations



$$\underbrace{v_w(t)}_{\text{Voltage across winding}} = \underbrace{i_w(t)R}_{\text{Voltage across resistance}} + \underbrace{L\,\frac{d}{dt}i_w(t)}_{\text{Voltage across inductor}} + \underbrace{k_t\dot{\psi}(t)}_{\text{Back-EMF voltage}}$$

Solved second – using $i_w(t)$, solve for $v_w(t)$

$$\underbrace{k_t i_w(t)}_{\text{Motor torque}} = \underbrace{J_m\ddot{\psi}(t)}_{\text{Torque to accelerate inertia}} + \underbrace{b_m\dot{\psi}(t)}_{\text{Torque lost to friction}} + \underbrace{T_x(t)}_{\text{Motor output torque}}$$

Solved first – you know $\dot{\psi}(t)$ and derivatives → solve for $i_w(t)$

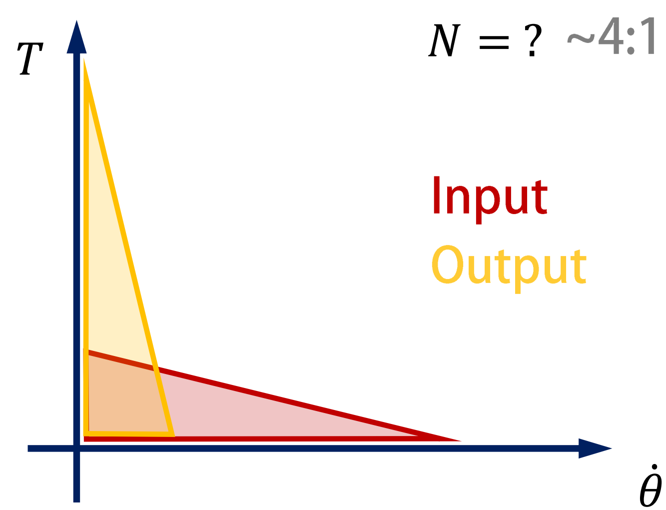
Initial Modeling Transmissions

Velocity = $\dot{\psi}$
Torque = T_w

→ **Transmission**
Ratio = N
Efficiency = η →

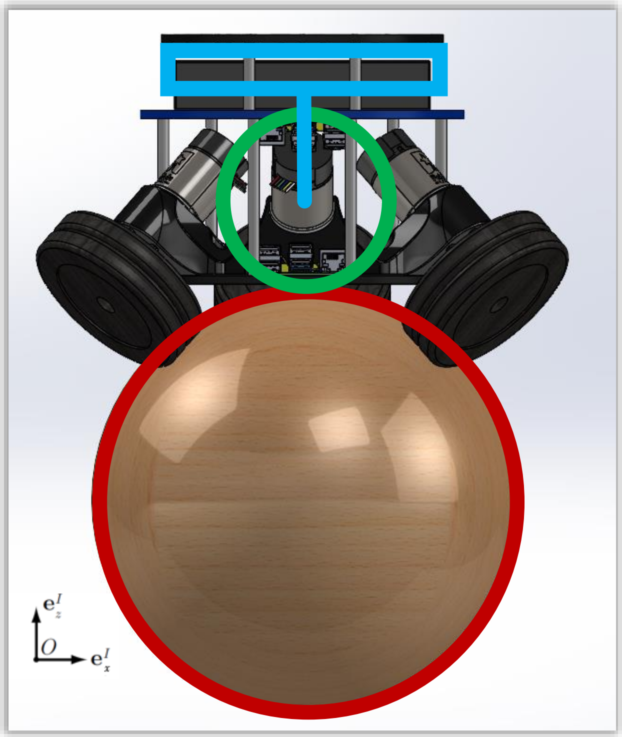
Velocity = $\dot{\psi} \cdot N$
Torque = $\frac{T_w}{N \cdot \eta}$

- Transmissions are used to trade torque for speed (effort for flow)
- Transmissions are parameterized by their ratio and efficiency
- The ratio is often selected in tandem with the motor to produce the required torque-speed (or force-speed)
- Transmissions scale torque and speed inversely
- Usually input speed >> output speed
- Usually input torque << output torque
- Lets think about a cartoon example



Ball-Bot Modeling

- We then learned how to model the expected requirements for ball-bot motion
- These can be found using many tools: estimating, direct measurements, online resources, datasheets, intuition
- We measured / looked up:



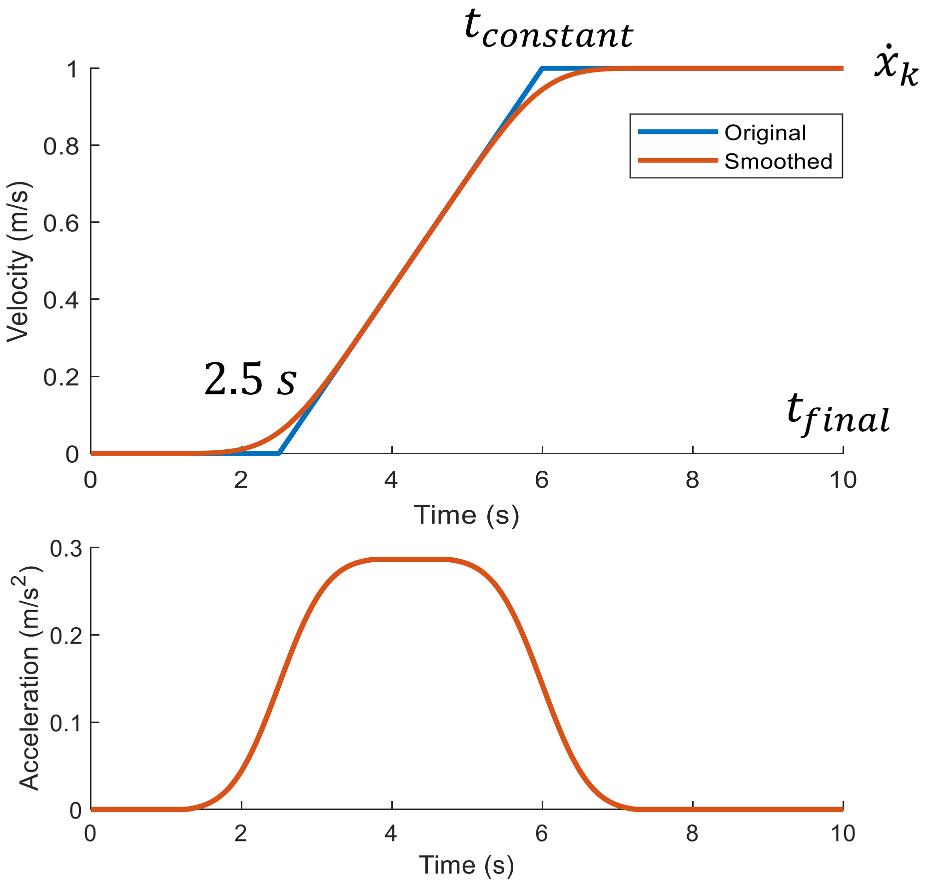
Body / chassis:
- Distance to CoM: $L = 0.23\ m$
- Mass: $m_A = 1.71\ kg$
- Moment of inertia in x and y planes: $I_{x,y} = 0.01\ kgm^2$
- Moment of inertia in z plane: $I_z = 0.017\ kgm^2$

Wheel:
- Mass: $m_w = 0.29\ kg$
- Radius: $r_w = 0.1\ m$
- Moment of inertia: $I_w = 0.001\ kgm^2$

Ball:
- Mass: $m_k = 0.62\ kg$
- Radius: $r_k = 0.12\ m$
- Moment of inertia: $I_k = 0.004\ kgm^2$

Creating Expected Motion

- To determine the expected torque / speed and current / voltage, we need to have an expectation of the task—what will the motor do?
- If we want to predict the torque required, we need to generate a motion profile.
- We choose this when spec'ing the task
  - How long do we want it to take?
  - Final velocity: $\dot{x}_k^{final} = 1\,\frac{m}{s}$
  - Ramp duration: $3.5\ s$
  - Resulting acceleration
  - What does this say about current and voltage needed?
    - Acceleration ~ Torque ~ Current
    - Velocity ~ Voltage

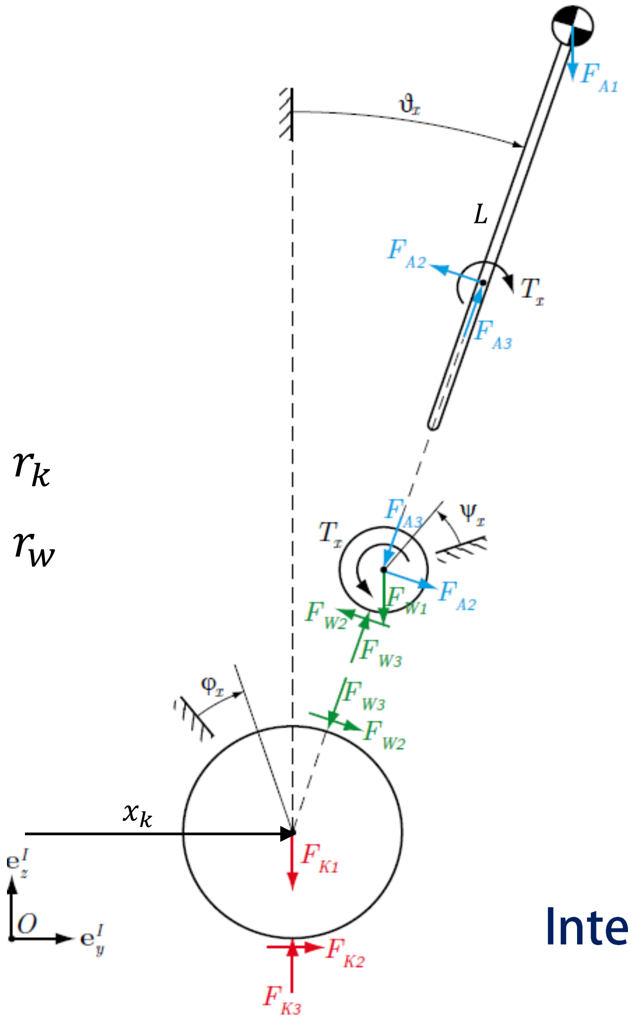


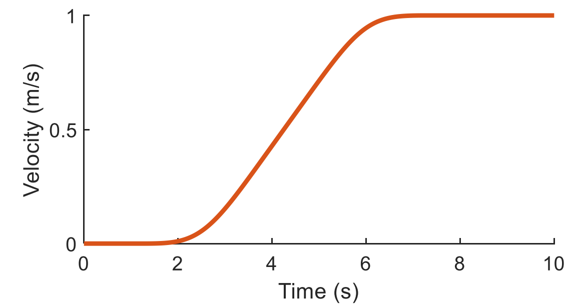
Ball-Bot Modeling

$$F_{K1} = g \cdot m_k$$

$$F_{W1} = g \cdot m_w$$

$$F_{A1} = g \cdot m_a$$





Ball radius r_k

Wheel radius r_w

Constraints:

$$x_k = r_k \varphi$$

$$\psi = \frac{r_k}{r_w}(\varphi - \vartheta) - \vartheta$$

Ball velocity: $\dot{\varphi} = \dfrac{\dot{x}_k}{r_k}$

Intermediate var: $\gamma = L \cdot m_a + (r_k + r_w) \cdot m_w$

Tangential contact force : $F_{W2} = (m_a + m_w) \cdot (g \cdot \sin(\vartheta) - r_k \ddot{\varphi} \cos(\vartheta)) - \gamma \ddot{\vartheta}$

Mechanical Modeling of a Planar Ball-Bot

$$\gamma = L \cdot m_a + (r_k + r_w) \cdot m_w$$

$$F_{W2} = (m_a + m_w) \cdot (g \cdot \sin(\vartheta) - r_k \ddot{\varphi} \cos(\vartheta)) - \gamma \ddot{\vartheta}$$

From free body diagram

$$\dot{\varphi} = \frac{\dot{x}_k}{r_k}$$

$$\psi = \frac{r_k}{r_w}(\varphi - \vartheta) - \vartheta$$

Constraints

Required current

Output torque to roll ball / mass

Torque to accelerate motor inertia

Torque to overcome viscous loss in motor

$$i_w = \frac{\frac{T_x}{N\eta} + JN\ddot{\psi} + bN\dot{\psi}}{k_t}$$

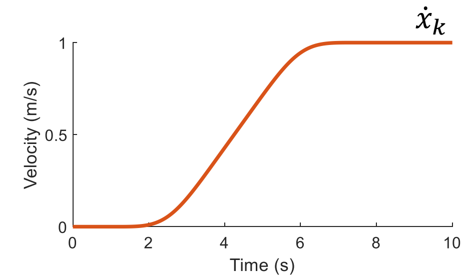
Required voltage

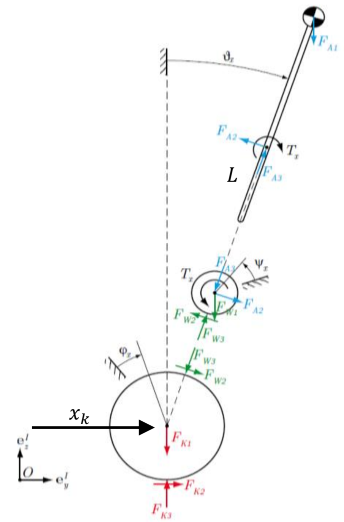
Voltage drop across resistance

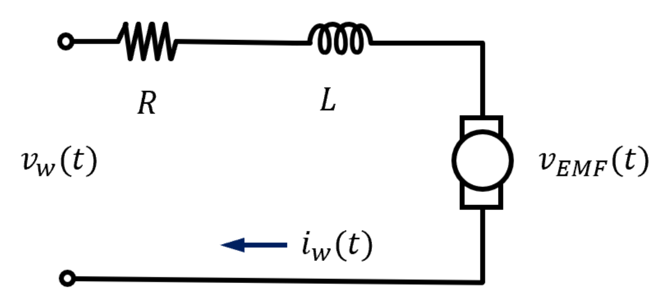
Back EMF voltage

Voltage drop across inductance

$$v_w = i_w R + k_t N \dot{\psi} + L \frac{di_w}{dt}$$



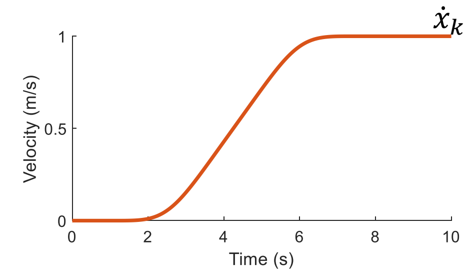




Mechanical Modeling of a Planar Ball-Bot

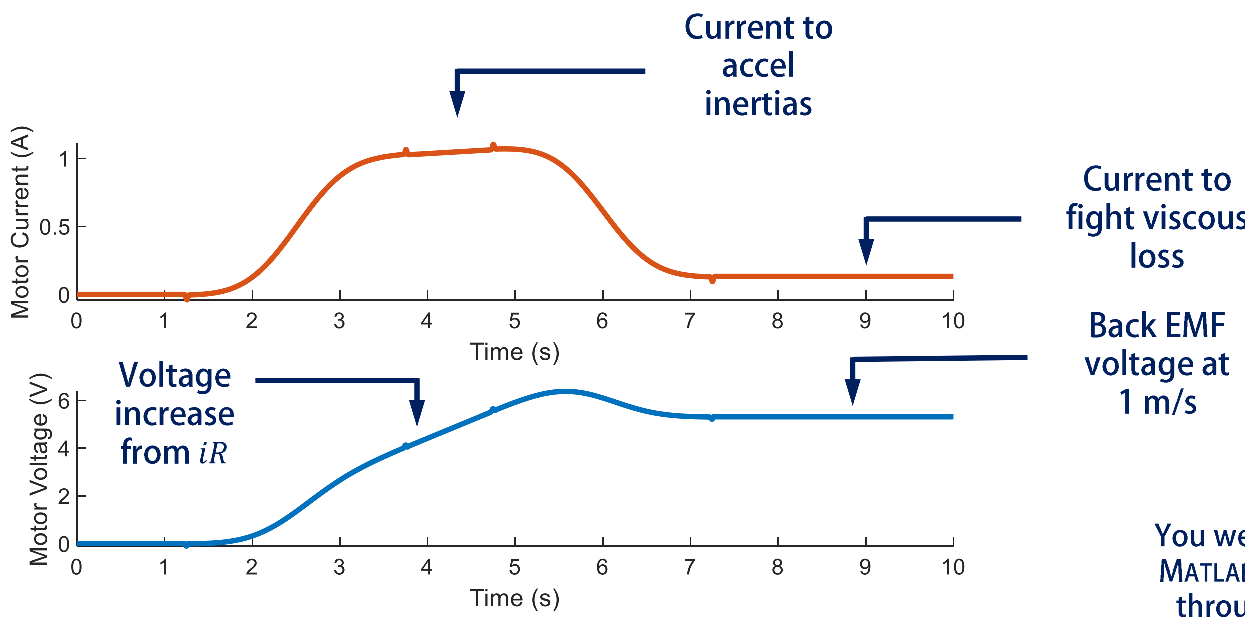
$$\gamma = L \cdot m_a + (r_k + r_w) \cdot m_w$$

$$F_{W2} = (m_a + m_w) \cdot (g \cdot \sin(\vartheta) - r_k \ddot{\varphi} \cos(\vartheta)) - \gamma \ddot{\vartheta}$$



$$\dot{\varphi} = \frac{\dot{x}_k}{r_k} \qquad \psi = \frac{r_k}{r_w}(\varphi - \vartheta) - \vartheta$$

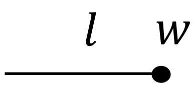
$$i_w = \frac{\frac{T_x}{N\eta} + JN\ddot{\psi} + bN\dot{\psi}}{k_t} \qquad v_w = i_w R + k_t N \dot{\psi} + L\frac{di_w}{dt}$$



You were provided with MATLAB code that walks through this analysis

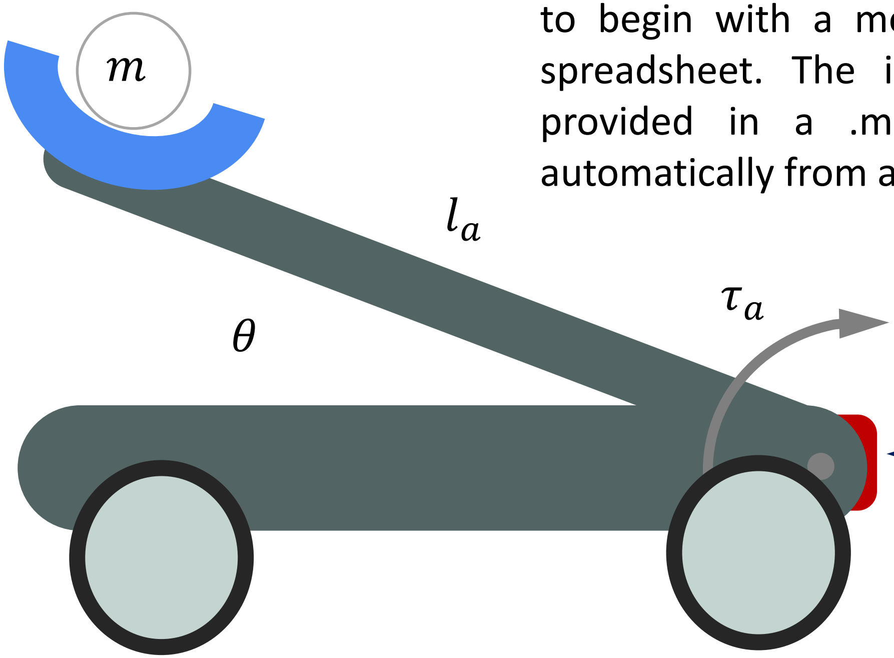
M ROBOTICS

Example Midterm Question



$J = wl^2$

Goal: Determine the motor current, voltage, torque, and speed for the task. You will need to begin with a motor from the provided spreadsheet. The input (theta) has been provided in a .mat file that will load automatically from a starting script provided.



$$m = 10\ kg$$
$$l_a = 1\ m$$
$$\eta = 0.8$$

$$k_t i_w = \tau = \left(J + \frac{m l_a{}^2}{\eta N^2}\right)\ddot{\varphi} + b\dot{\varphi} + \frac{mgl\cos\theta}{\eta N}$$

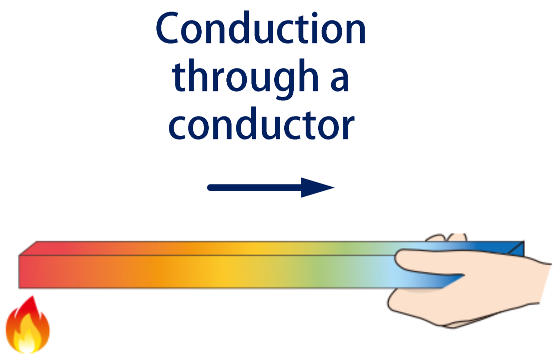
$$i_w = \frac{\left(J + \frac{m l_a{}^2}{\eta N^2}\right)N\ddot{\theta} + bN\dot{\theta} + \frac{mgl\cos\theta}{\eta N}}{k_t}$$

$$\varphi = N\theta$$

$$v = i_w R + k_t N\dot{\theta} + L\frac{di_w}{dt}$$

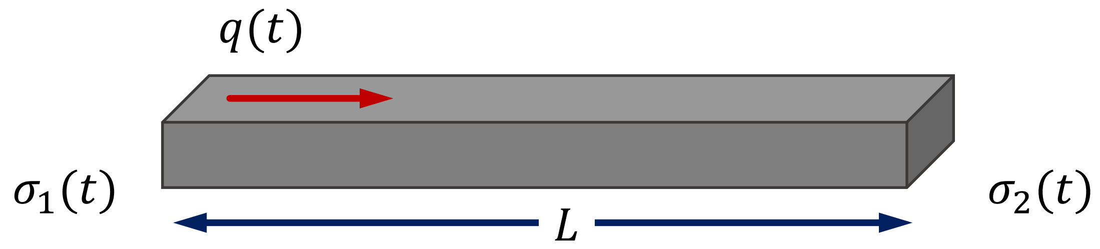
Thermal Modeling

- The last step in the spec'ing process was to understand the thermal demands
- Heat flows from the motor windings to the housing to the atmosphere
- This includes two types of heat transfer
    - **Conduction** – heat energy exchange between two objects
    - **Convection** – transfer of heat energy between an object and the environment
- Convection and conduction have the same underlying governing equations
- If we understand the equations, we can predict the motor winding temperature



Thermal Modeling

- Conduction - heat flux $q(t)$ in Watts – comes from $i_w^2 R$ from motor windings



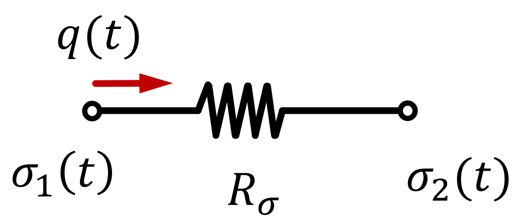
- Thermal resistivity, units K/W is below, using thermal conductivity κ (W/mK)

$$R_\sigma = \frac{L}{A\kappa}$$

- Thus,

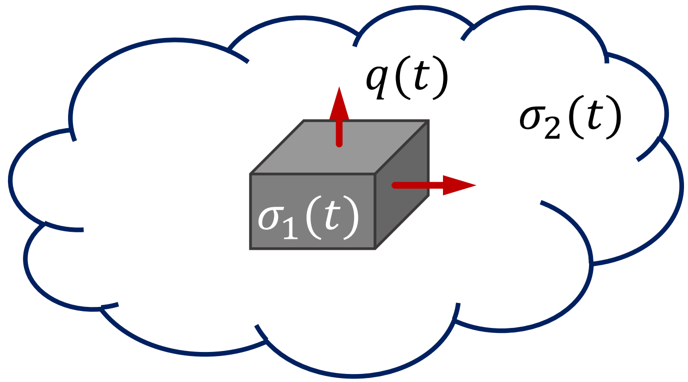
$$q(t) = \frac{\sigma_1(t) - \sigma_2(t)}{R_\sigma}$$

This looks familiar - Thermal version of Ohms Law



Thermal Modeling

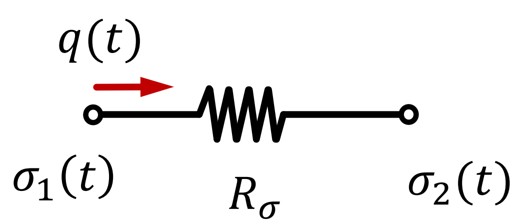
- Convection



- Convection has identical governing equations
- Consider an object in the atmosphere with surface area A and convective heat transfer coefficient h (W/m^{2}C)

$$R_\sigma = \frac{1}{hA}$$

$$q(t) = \frac{\sigma_1(t) - \sigma_2(t)}{R_\sigma}$$



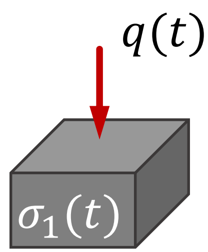
- R_σ can be changed with heat sinks, etc.

Thermal Modeling

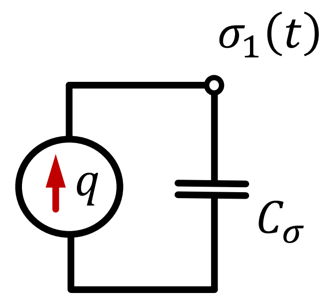
- Thermal capacitance (also called thermal mass)
- Describes an objects ability to store heat energy

$$C_\sigma = mc_p$$

- m is the objects mass and c_p is the specific heat (J/kgK)



$$q(t) = C_\sigma \frac{d}{dt}\sigma_1(t)$$



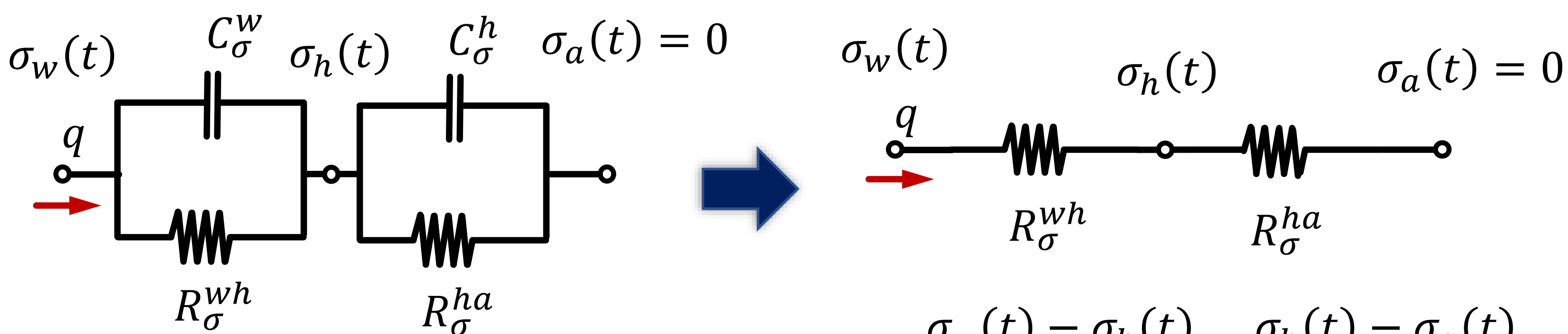
- Thermal systems have the same relationships as electrical systems
  - Voltage is analogous to temperature (effort)
  - Current is analogous to heat flux (flow)
  - Resistances and capacitances

Thermal Modeling

- Datasheets often provide the maximum continuous torque / current
- If you use these, your design will always work
- If you want to push the limits, the thermal analysis can be used to design systems that take advantage of the delay / dynamics of the system

5	Nominal torque (max. continuous torque)	mNm	94.6	94.2	92.9	
6	Nominal current (max. continuous current)	A	7.58	5.03	3.68	

- This is based on the forced response (steady state) solution to the thermal ODE
- In steady state, the system behaves like two resistors in series



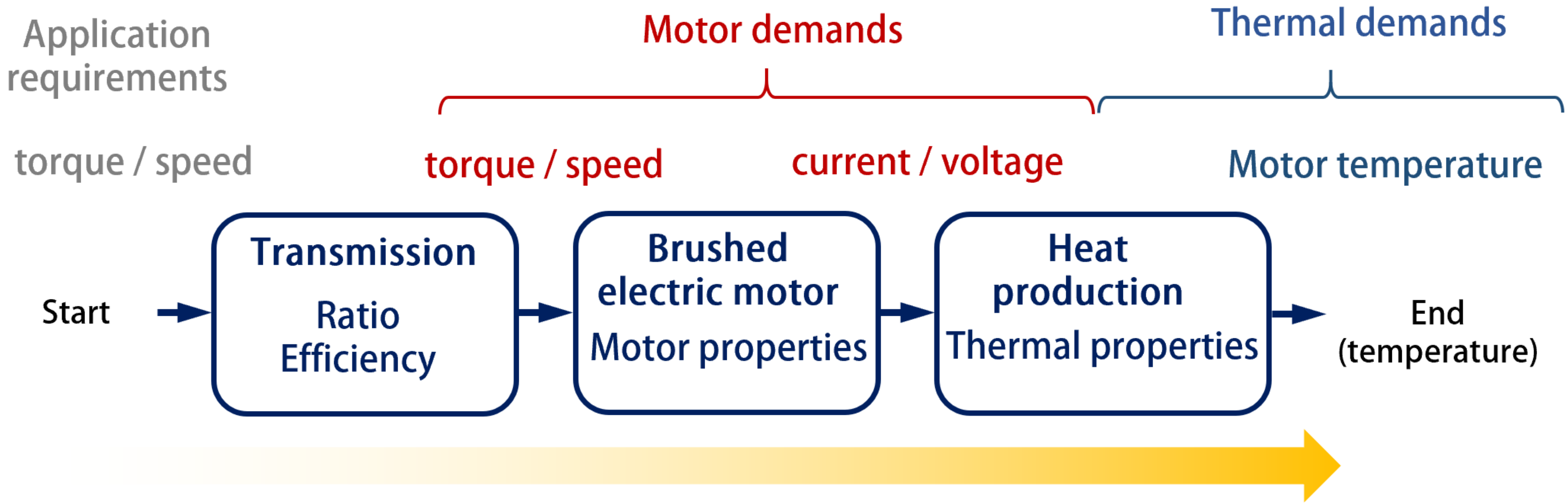
$$R_\sigma^{total} = R_\sigma^{wh} + R_\sigma^{ha}$$

$$\Delta\sigma = q(t)R_\sigma^{total} = q(t)\,(R_\sigma^{wh} + R_\sigma^{ha})$$

$$q(t) = \frac{\sigma_w(t) - \sigma_h(t)}{R_\sigma^{wh}} = \frac{\sigma_h(t) - \sigma_a(t)}{R_\sigma^{ha}}$$

Ohm's law

Overview



- Review of parameters needed for design framework
  - **Transmission** – efficiency (η)
  - **Motor** – resistance (R), inductance (L), torque constant (k_t), inertia (J), damping (b)
  - **Thermal** – thermal properties (R_σ^{total} or, R_σ^{wh} and R_σ^{ha}) or continuous current / torque for steady state analysis
  - **You choose** – application requirements, motor, transmission ratio (N), maximum voltage


Manufacturing
FDM
SLA
Polyjet
Laser Cutter
Water Jet

Manufacturing Types

"spec'ing"
This happens first

Now you know:
- Torques
- Speeds
- Ratio
- Rough sizing

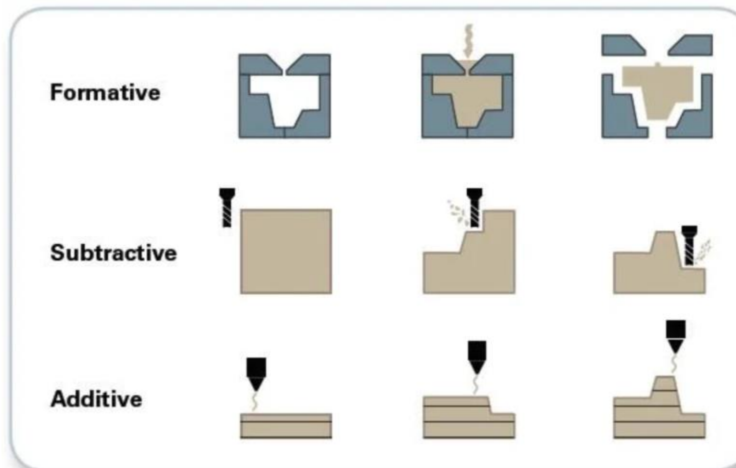
Second focus of the class

Transmission — Ratio, Efficiency → **Brushed electric motor** — Motor properties → **Heat production** — Thermal properties → **Physical Design** — Layout, Manufacturing

- So far, we learned to spec the components – we've chosen the architecture and now we need to make it a reality
- This includes choosing the physical layout, solid modeling, creating design files, and manufacturing
- We went over manufacturing first for the sake of lab
- There are three types of manufacturing
    - Formative
    - Subtractive
    - Additive

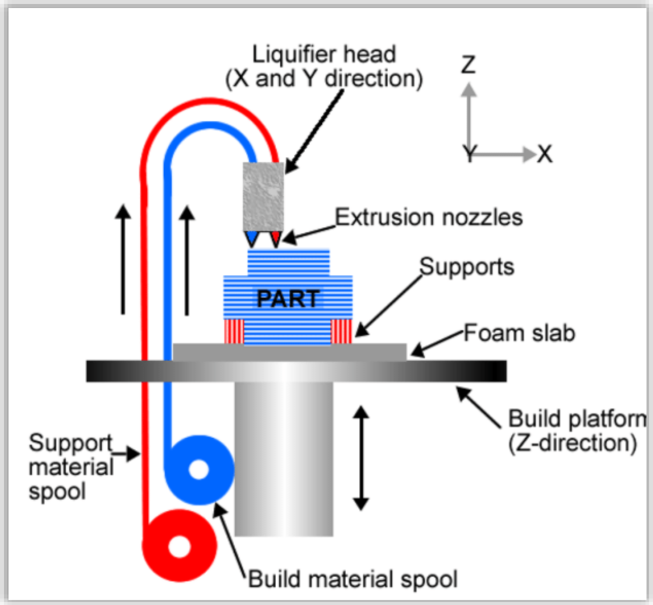
Some

What we will focus on in this course



Fused Deposition Modeling (FDM)

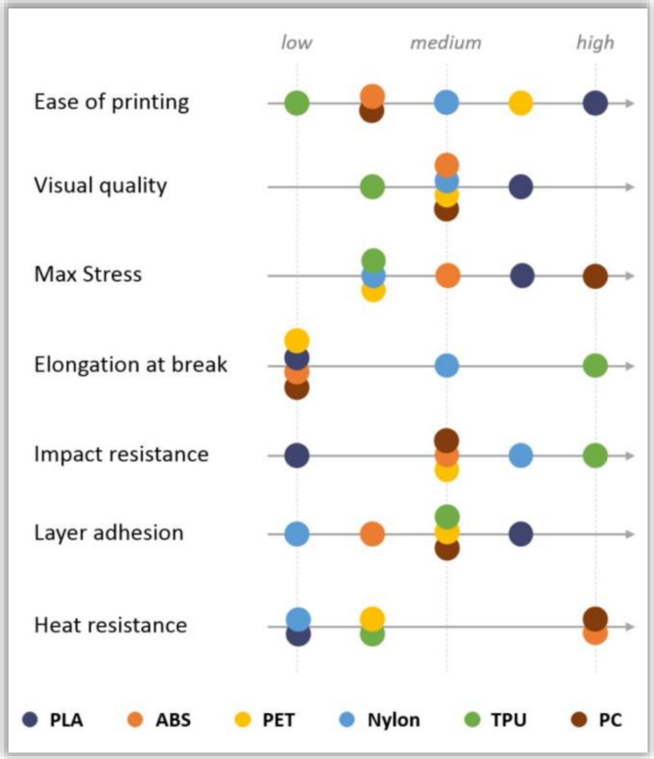
- One of the most common types 3D printers
- Heated plastic filament is extruded through a nozzle
- Common plastics: ABS, PLA, nylon
- Uses support material alongside build material to support parts they print
- Machine costs $100s to $10,000s



- Characteristics:
  - Layer thickness: 0.1mm ~ 0.5 mm
  - Build volume: 10 x 10 cm^2 ~ 50 x 50 cm^2+
  - Materials: next slide
  - Composite available
    - Continuous
    - Chopped

Fused Deposition Modeling (FDM)

- **PLA** – Thermoplastic monomer that is strong and easy to print, nice finish, good UV resistance
- **ABS** – Better temp resistance than PLA with higher toughness, can be processed with acetone for gloss finish
- **PET** – Heavier than PLA and ABS, with high chemical resistance
- **Nylon** – Strong material with some anisotropy. Mixed with glass or carbon fiber in Markforged



3D Hubs

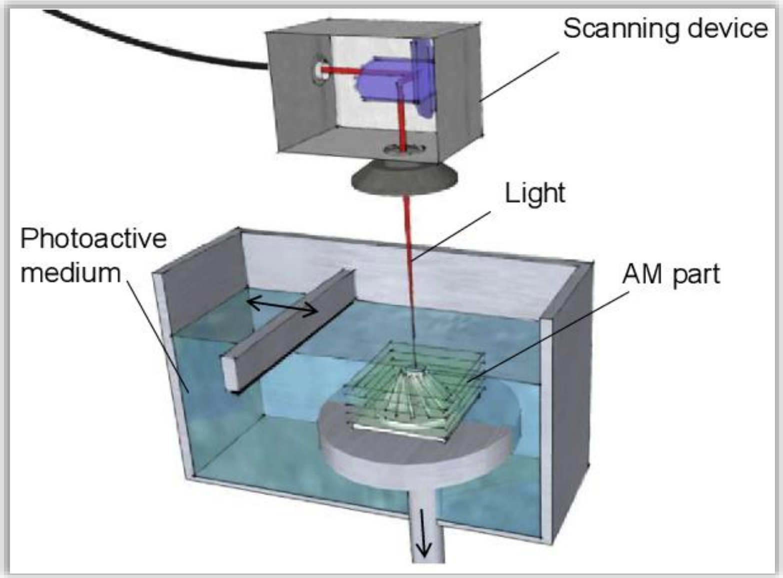
$800 Prusa (ABS)

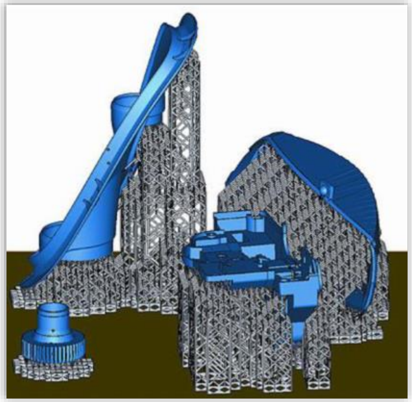
$50k Markforged (Onyx) - with continuous fiber composite reinforcement

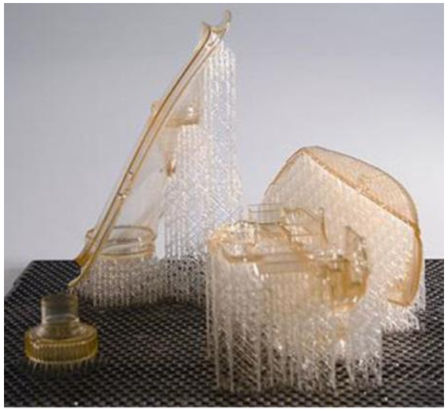
Stereolithography (SLA)

Formlabs Form 3

- SLA uses a liquid photoactive resin
- Laser cures / solidifies a thin layer of material at the focused depth
- The part descends (rather than the part building up)
- Support structure is built like a lattice and broken off
- Cost: \$100+
- Layer thickness: 50 μm
- Build volume: can be very large
- Materials: photopolymers (clear, opaque, range of material properties)
- Variants on SLA printers (DLP) – faster by using an image not a laser

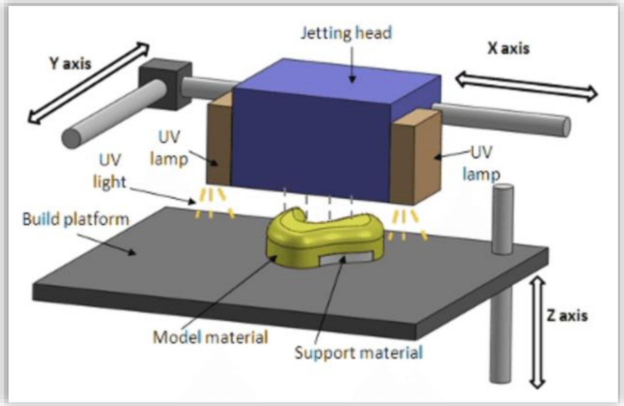






Polyjet Printers

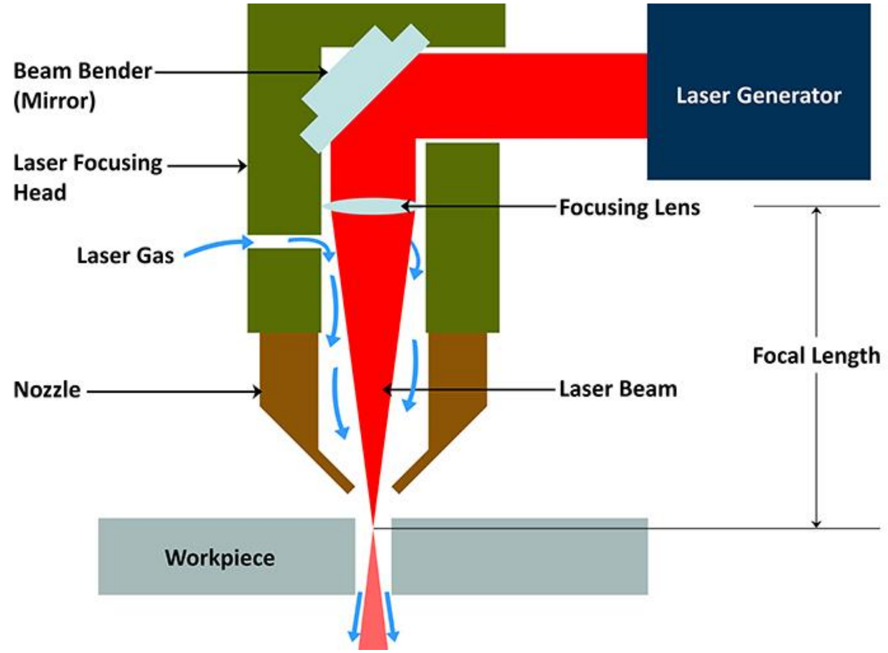
- Polyjet printers print like an inkjet printer
- They spray material and cure with a UV light
- Invented by Stratasys
- Benefit: multiple colors and hardness / durometers
- Rubbery parts
- Support material often removed with ultrasonic water bath
- Cons: Parts are UV sensitive and get brittle
- Cost: $100+
- Layer thickness: 10s of μm
- Build volume: up to ~100 x 100 cm
- Materials: photopolymers (clear, opaque, range of material properties)



Stratasys Connex 500

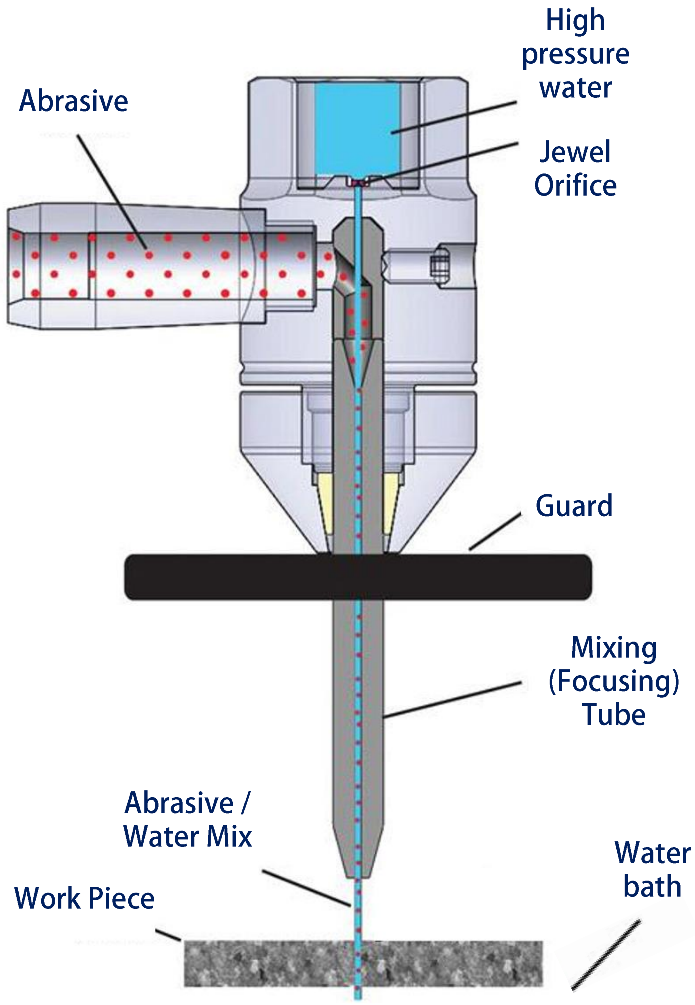
Laser Cutters

- A laser cutter focuses a laser onto the surface of a part
- Can cut detailed parts as well as raster images (2D)
- Protective gas layer
- The cut has some slight width due to the laser
- Known as “kerf”
- Three types of laser cutters
    - **CO_2 lasers** – tubes containing specialized gas produce a laser that is focused on the part. Power ranges from 25 – 100 W. Cuts most organics, some plastics, and some thin metals
    - **Fiber lasers** – Solid state laser enabling a small focal diameter. Up to 100x more powerful than CO_2 lasers, and versatile, being able to cut metal.
    - **Nd:YAG / Nd:YVO lasers (Neodymium lasers)** – powerful lasers with a narrow focal length used to cut many materials, even some ceramics

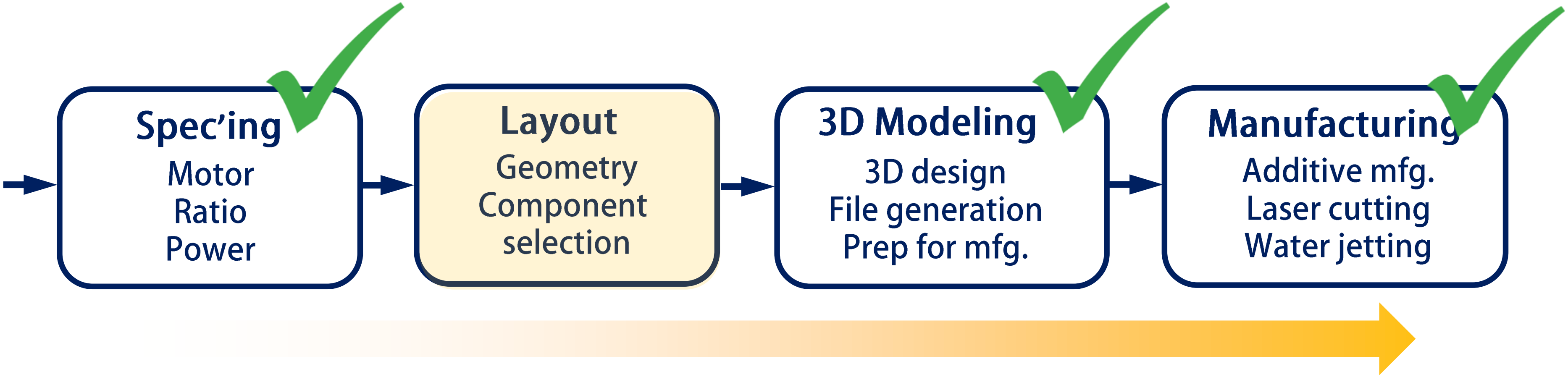


Water Jet Cutter

- Water jet cutting can be used to create metal parts with similar design advantages as laser cutting
  - Simple 2D designs
  - Quick, convenient prototyping
- Anatomy of a water jet cutter
- Key benefit: works on thick metals
- Metal is cut by high pressure stream of water and abrasive garnet
- Water jet cutters can cut many materials, including all metals, plastic, rubber, glass, CF, etc.
- Materials can be thick (< 25 mm)
- No heat affected zones (doesn't alter properties)
- Reasonably consistent edge quality



Manufacturing Types



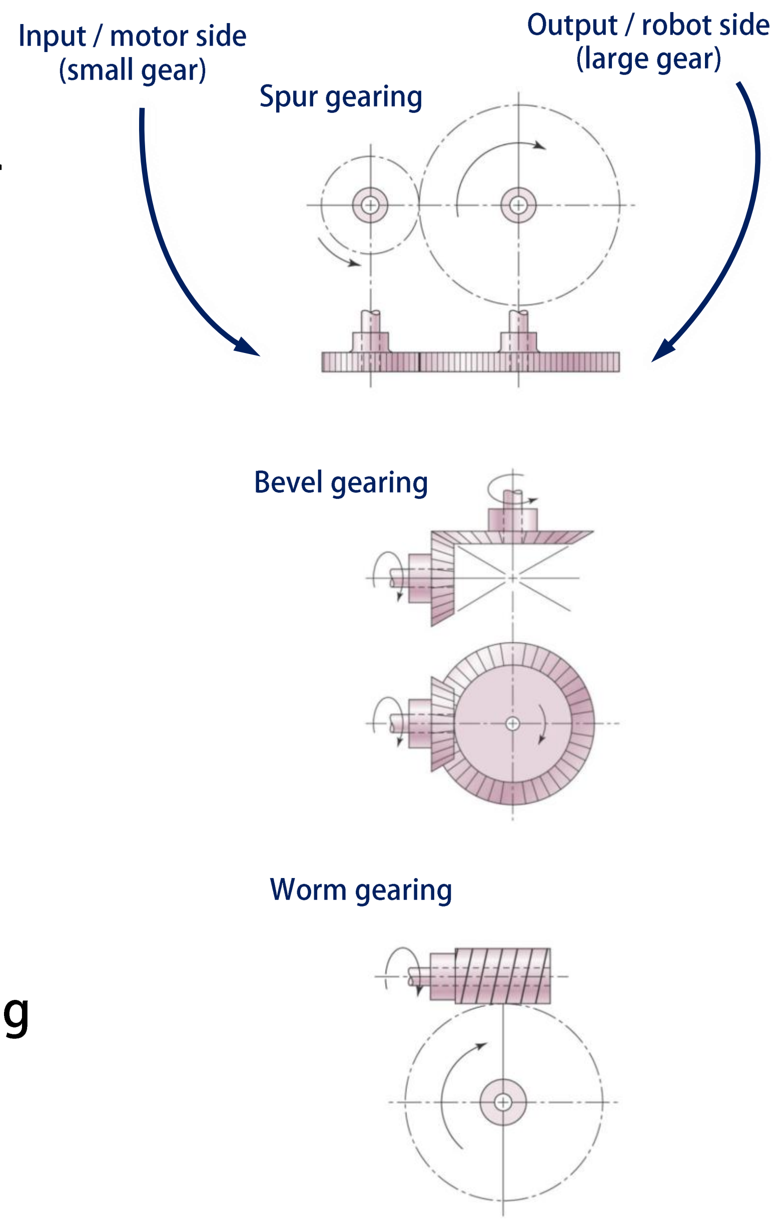
- We've learned how to spec and make robots, now lets talk about design layouts
- This is often moving motion from one place to another (kinematics)
- In robots, motion moving from the actuator to the end effector
- It begins with understanding the geometry of your robot and transmissions
- Very application specific!

Understanding Motion

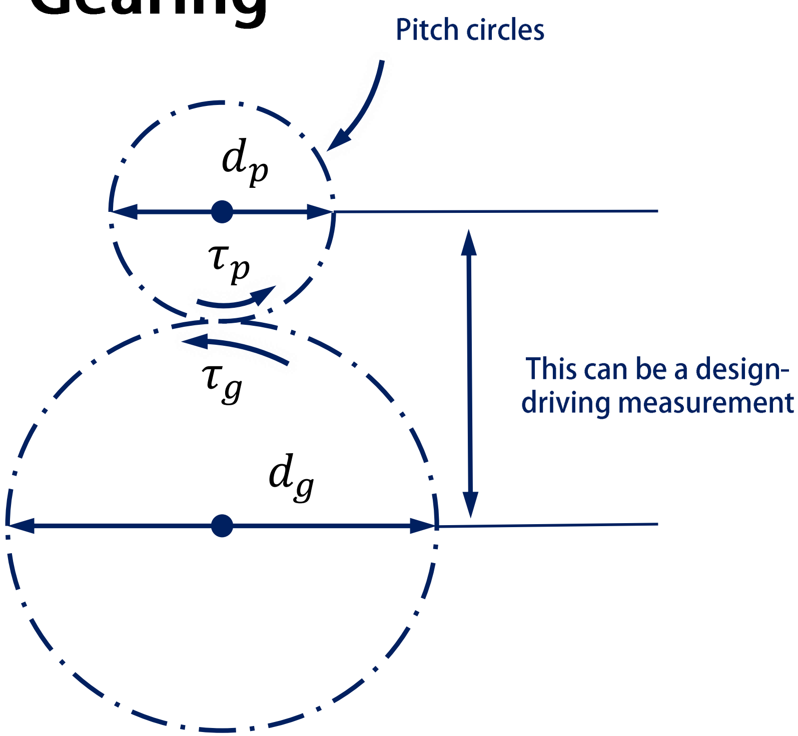
- To determine layout, first we need to understand the required motion in our robot design
- Motion can be rotational (more common) or linear (more difficult)
- At this point, you know your desired motor and transmission ratio
- We need to package this ratio in the proper form factor for your robot
- Many types of transmissions
  - Gearing (spur, bevel, worm, etc.)
  - Belt drives
  - Screws
  - Linkages
- Often there are geometric constraints in addition to ratio constraints
  - Does motion need to be somewhere specific?
  - For the ball-bot, this is very important

Gearing

- Backdrivable and non-backdrivable: whether negative power can be transmitted through the transmission.
  - Efficiency
  - Pressure angle / friction cone
  - Implications? No energy regeneration
- **Spur gears** – teeth parallel to the axis of rotation, transmitting motion from one shaft to another (parallel) shaft
- **Bevel gears** – teeth on conical surfaces, which transmit motion between two perpendicular shafts
- **Worms and worm gears** – high ratio gearing that transmits motion between two perpendicular / offset shafts



Gearing



Diametral pitch

Circular pitch

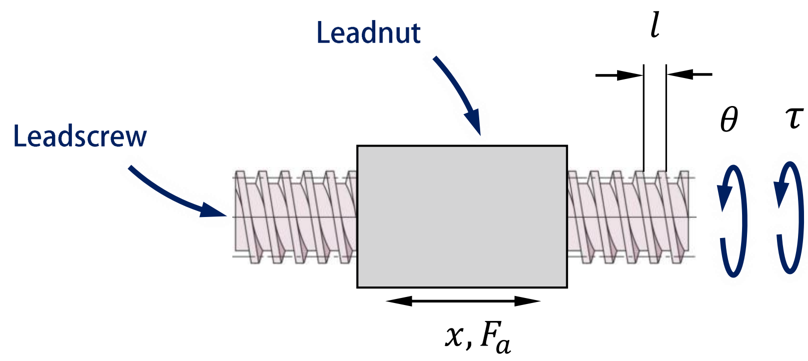
$$\left.\begin{array}{l} P = \dfrac{n}{d} \\[2ex] p = \dfrac{\pi d}{n} \end{array}\right\} \text{Pertains to individual gears}$$

$$\left. N = \frac{d_g}{d_p} = \frac{n_g}{n_p} = \left|\frac{\omega_p}{\omega_g}\right| = \frac{\tau_g}{\eta \tau_p} \right\} \text{Pertains to gearsets}$$

- Pinion teeth, n_p – number of teeth on pinion
- Gear teeth, n_g – number of teeth on gear
- Transmission ratio, N – ratio of input speed to output (also diameters, torque, ...)
- Conjugate action – defines that the ratio of velocity is inversely proportional to the pitch radii

Screws

- Screws turn rotary motion into linear motion
- Useful in a wide array of robotics applications
- Lead screws are low cost and useful
- Can be purchased as a set with specified dimensions
- More information required to know full transmission ratio
- Ball screws can be used for highly efficient motion (expensive)



$$\tau = \frac{F_a l}{2\pi\eta}$$

η	Efficiency
F_a	Thrust force
l	Screw lead
τ	Driving torque

$$\dot{x} = \frac{l\dot{\theta}}{2\pi}$$

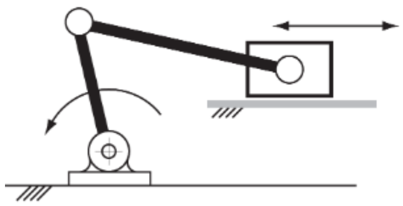
$\dot{x}$	Nut linear velocity
$\dot{\theta}$	Shaft angular velocity

leadscrew

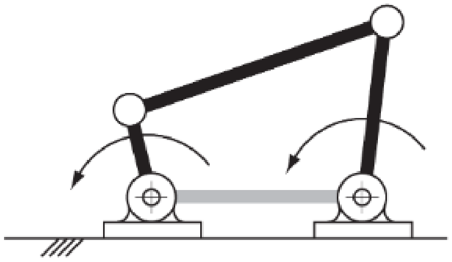
ballscrew

Linkages

- Example linkage types (more [here]())
- First step is determining the input and output links
- Determine transmission ratio and kinematics as a function of starting configuration and link lengths
- Kinematics / transmission ratio determined using geometry
- L_3 is input, L_1 is output

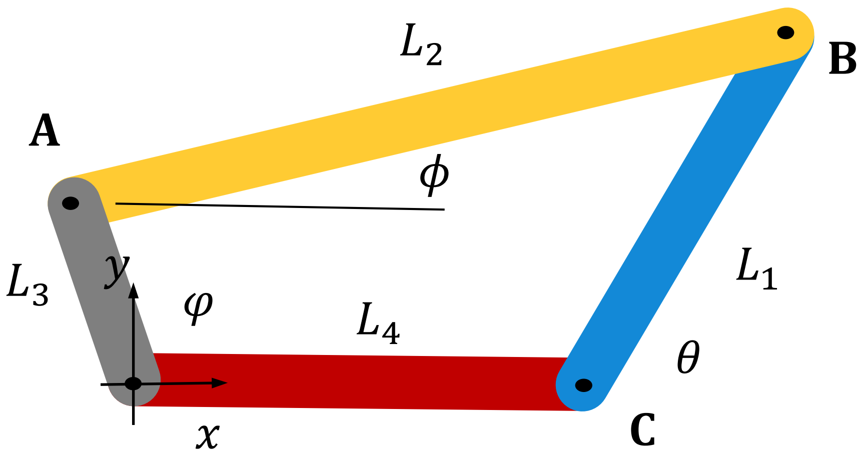


Slider crank



Parallelogram 4-bar

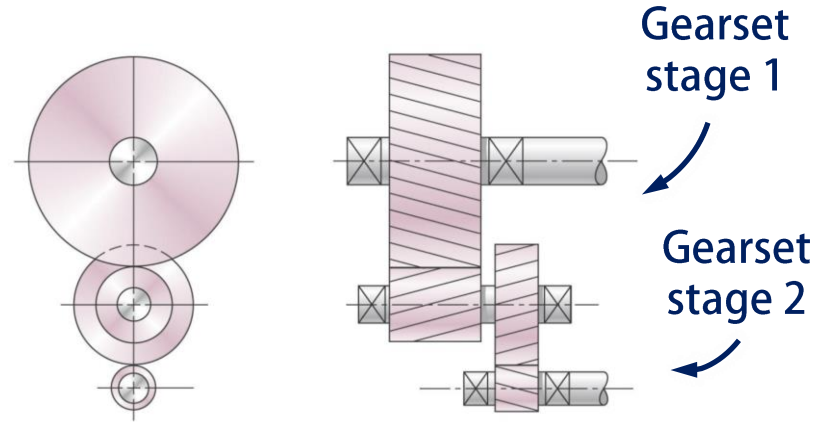
Many more…



Compound Transmissions

- Sometimes, larger ratios are needed
- This can be accomplished by stacking transmissions
- Known as *compound transmissions*
- Shown as gears, but could be any type
- Ratios are multiplied
- Efficiencies are multiplied
- Extends to an arbitrary number of stages

- Next, we learned about the layout, kinematics, and kinetics used to describe the ball-bot



$$\underbrace{\boxed{\begin{array}{c}\text{Gearset 1}\\ N_1, \eta_1\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Gearset 2}\\ N_2, \eta_2\end{array}}}$$

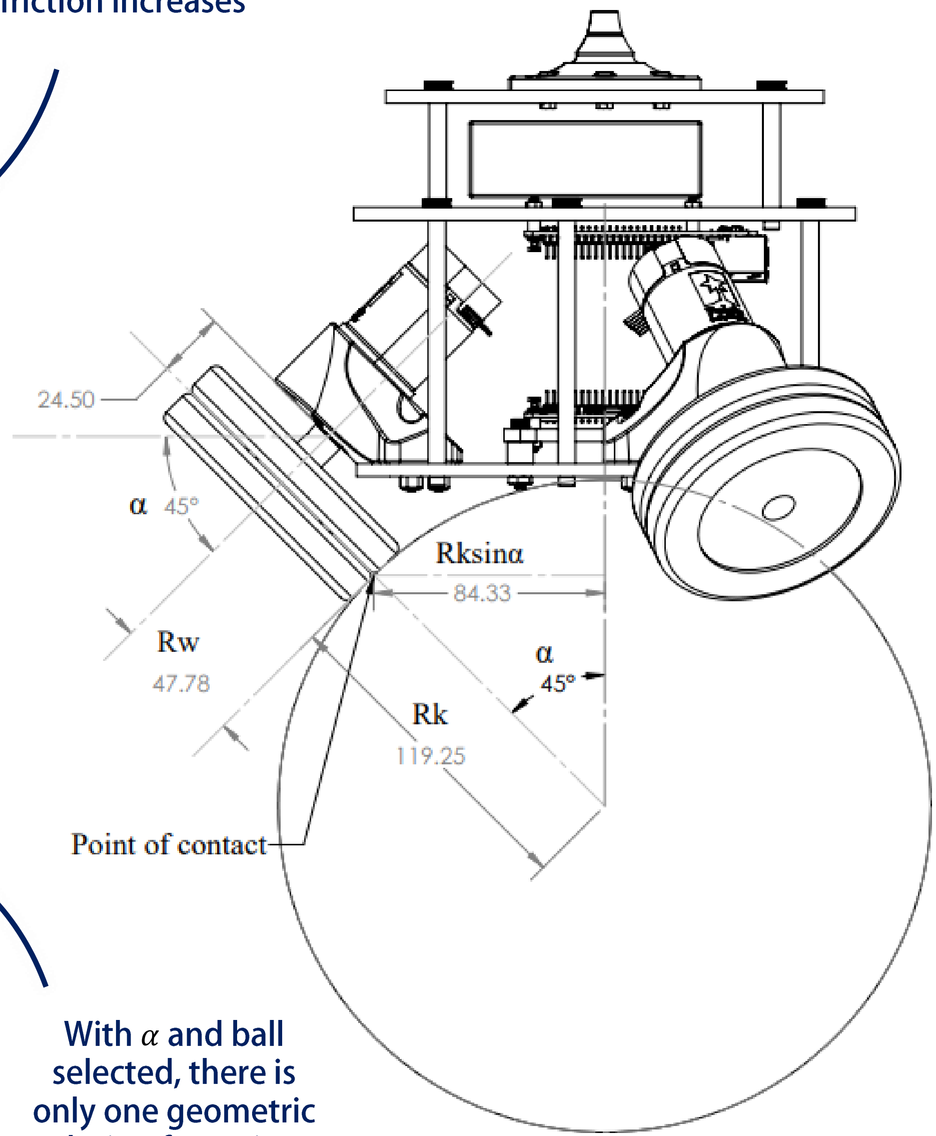
Compound transmission

$$N_{total} = N_1 \cdot N_2$$
$$\eta_{total} = \eta_1 \cdot \eta_2$$

Ball-Bot Layout

Balances base width with radial force / friction increases

- Major design decisions are α angle, ball radius, and wheel radius
- We chose $\alpha = 45^{\circ}$
    - As α is increased, radial force increases → more friction
    - Larger α designs have a greater lean angle
- We chose a basketball for its cost, size, and texture
- Basketball radius (R_k) is 119.25 mm
- Wheel radius (R_W) is 47.8 mm
- Coupler to wheel center distance is 24.5 mm
- Wheel contacts spaced on circle with radius 84.3 mm from Z axis $(R_k \sin(\alpha))$



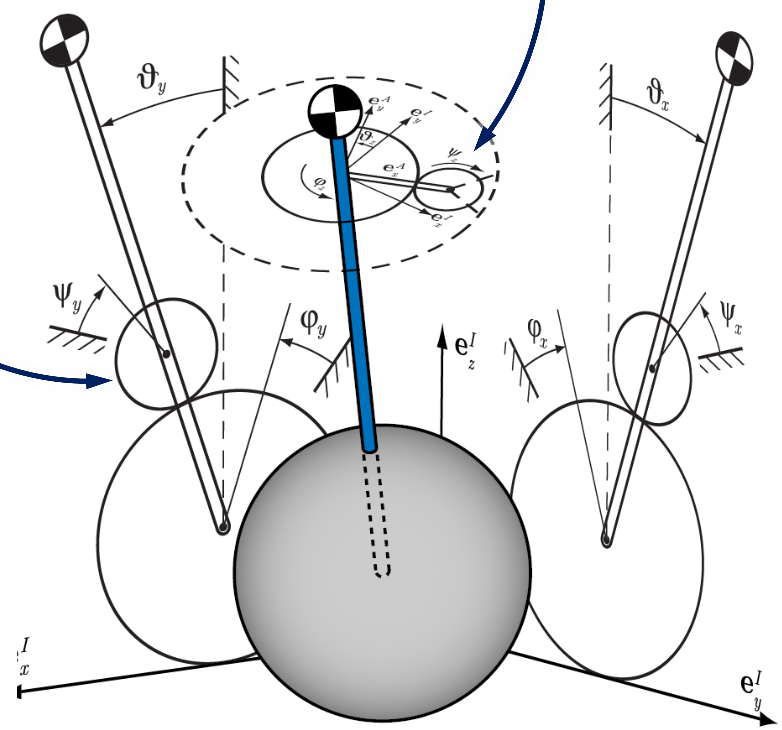
With α and ball selected, there is only one geometric solution for a given wheel radius

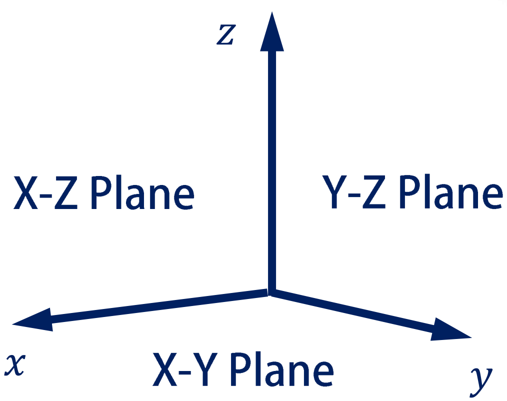
Full Planar Model

The X-Y plane contains a single wheel that rotates the ball-bot

ϑ_{axis}	Body rotation
ψ_{axis}	Wheel rotation
φ_{axis}	Ball rotation

The X-Z and Y-Z planes have a single wheel beneath the center of mass

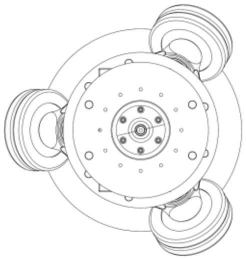




Since we want to balance and drive, the rotation of the ball (i.e. X-Y plane) may be irrelevant

- Each plane has two DOFs: Rotations of the chassis and ball
- X-Z and Y-Z planes are required for balance and motion—we will focus on these
- The torques and motion of the virtual wheels are different from the real wheels

Relating Virtual and Real Torques



- Torque in both coordinate systems is conserved

$$T_1 + T_2 + T_3 = T_x + T_y + T_z$$

- Written in terms of force and perpendicular distance

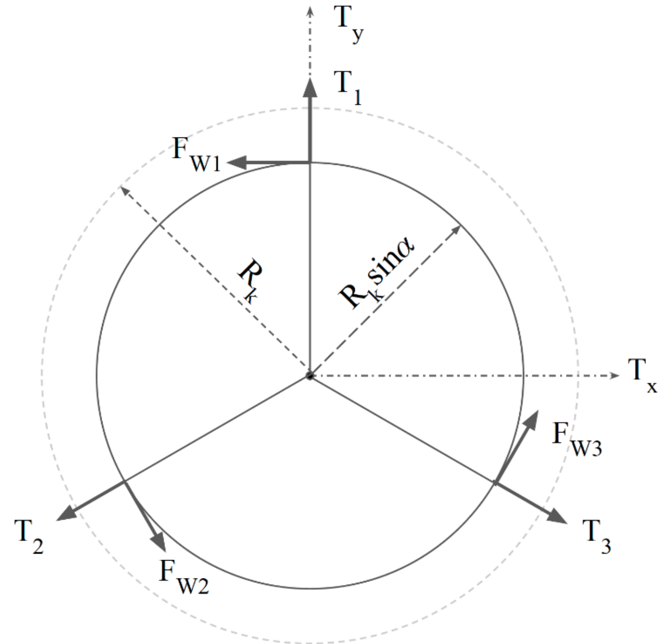
$$r_{W1} \times F_{W1} + r_{W2} \times F_{W2} + r_{W3} \times F_{W3} \ldots$$
$$= r_{Wx} \times F_{Wx} + r_{Wy} \times F_{Wy} + r_{Wz} \times F_{Wz}$$

- Solving for torques

$$T_1 = \frac{1}{3}\left(T_z - \frac{2T_y}{\cos(\alpha)}\right)$$

$$T_2 = \frac{1}{3}\left(T_z + \frac{1}{\cos(\alpha)}\left(-\sqrt{3}T_x + T_y\right)\right)$$

$$T_3 = \frac{1}{3}\left(T_z + \frac{1}{\cos(\alpha)}\left(\sqrt{3}T_x + T_y\right)\right)$$



Determined by solving conservation of torque using eqns. from previous slides

Relating Virtual and Real Torques

α $\pi/4$ or 45°

β $\pi/2$ or 90°

- Conversion equations provided in ETH Zurich dissertation
- Solved for real motor torques

These are the same equations as the previous slide, but written generally for any α and β

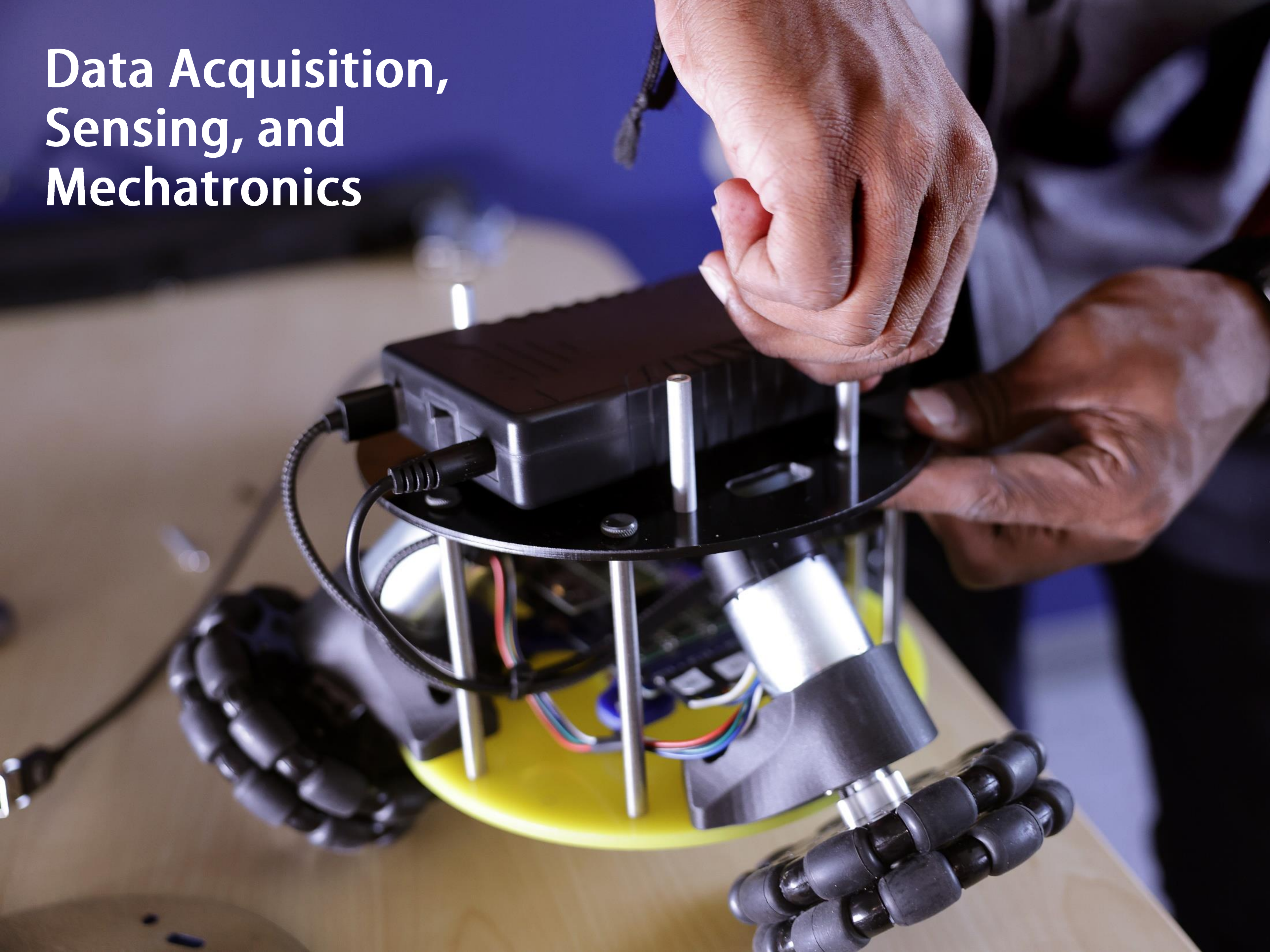
$$
\begin{aligned}
T_1 &= \frac{1}{3} \cdot \left(T_z + \frac{2}{\cos\alpha} \cdot (T_x \cdot \cos\beta - T_y \cdot \sin\beta) \right) \\
T_2 &= \frac{1}{3} \cdot \left(T_z + \frac{1}{\cos\alpha} \cdot \left(\sin\beta \cdot (-\sqrt{3}T_x + T_y) - \cos\beta \cdot (T_x + \sqrt{3}T_y) \right) \right) \\
T_3 &= \frac{1}{3} \cdot \left(T_z + \frac{1}{\cos\alpha} \cdot \left(\sin\beta \cdot (\sqrt{3}T_x + T_y) + \cos\beta \cdot (-T_x + \sqrt{3}T_y) \right) \right)
\end{aligned}
$$

- Solved for virtual motor torques

$$
\begin{aligned}
T_x &= \cos\alpha \cdot \left(T_1 \cdot \cos\beta - T_2 \cdot \sin(\beta + \frac{\pi}{6}) + T_3 \cdot \sin(\beta - \frac{\pi}{6}) \right) \\
T_y &= \cos\alpha \cdot \left(-T_1 \cdot \sin\beta - T_2 \cdot \cos(\beta + \frac{\pi}{6}) + T_3 \cdot \cos(\beta - \frac{\pi}{6}) \right) \\
T_z &= T_1 + T_2 + T_3
\end{aligned}
$$

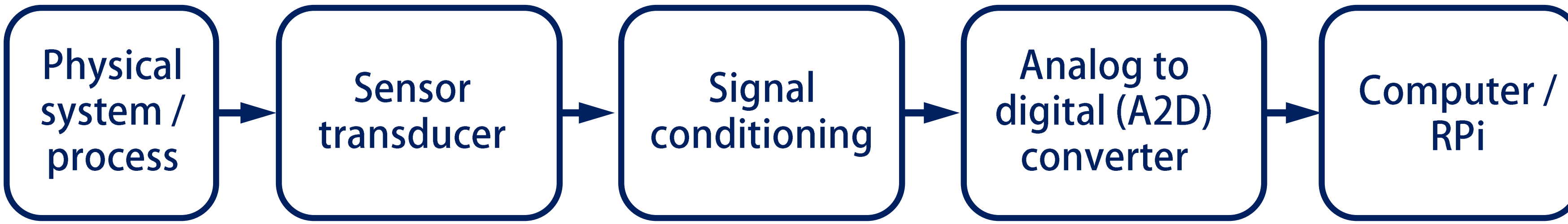
Fankhauser and Gwerder et al, 2010

Data Acquisition, Sensing, and Mechatronics



Data Acquisition

- Typically, sensors output voltage, which needs to be acquired by a digital computer for analysis and control
- Accomplished using a data acquisition system

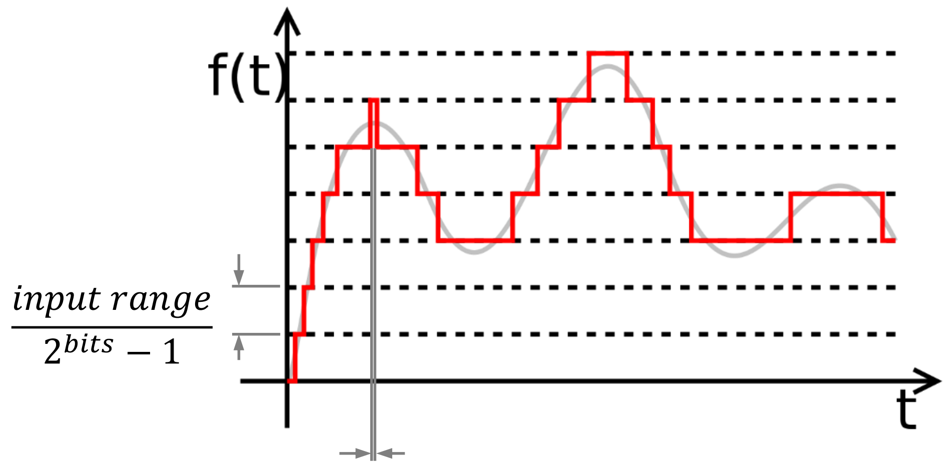


- Analog to digital (A2D) converter: digitizes voltage to be read by a computer
- Three key attributes
  - Bits – describes how many 'bins' can the voltage be separated into
  - Sample rate (Hz) – how fast the loop runs / A2D converter is sampled
  - Input range (V) – the total range of voltages able to be sampled

Resolution $\longrightarrow$ $$\frac{\Delta V}{bit} = \frac{V_{range}}{2^{bits} - 1}$$

Analog Data Acquisition

- Signals are sampled periodically, at a frequency governed by the sample rate
- This causes some ‘quantization’ of the analog signal
- The sample rate is a key factor of a data acquisition system
- It governs the frequency content of what can be measured
- Higher sample rates can sense higher frequencies
- Nyquist criterion:



$$\Delta t = \frac{1}{F_s} = \frac{1}{sample\ rate}$$

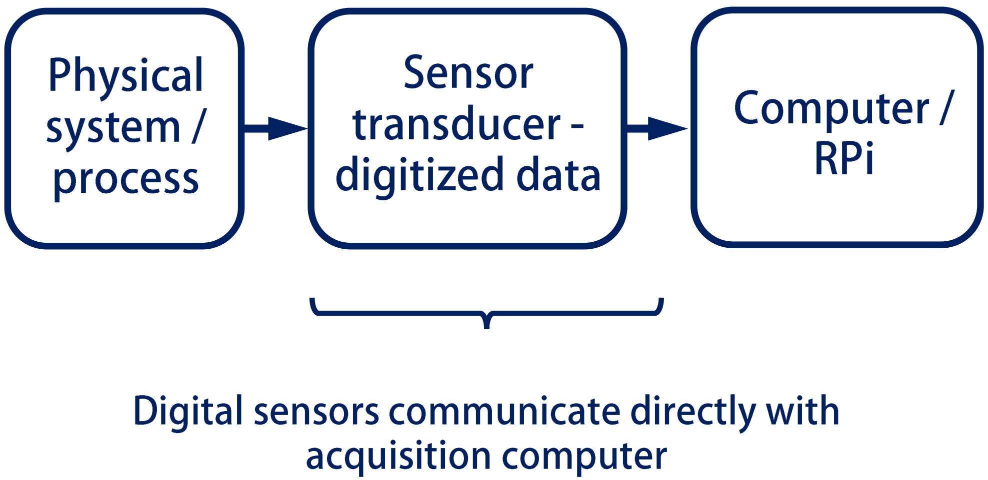
Maximum measurable frequency →

$$f_{max} = \frac{1}{2} F_s$$

- The highest frequency that can be measured is half the sample rate
- Sample rate / loop rate must be set carefully to make sure the relevant frequencies can be recorded

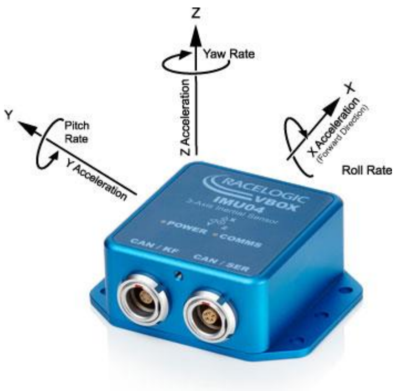
Digital Data Acquisition

- Digital sensors are becoming increasingly common
- Data are transmitted using digital communication (USB, I^2C, etc.)
- No analog voltage – concepts of resolution change for these sensors
    - Governed directly from the sensor, not the A2D card
- Nyquist frequency still applies
- Sampling still applies



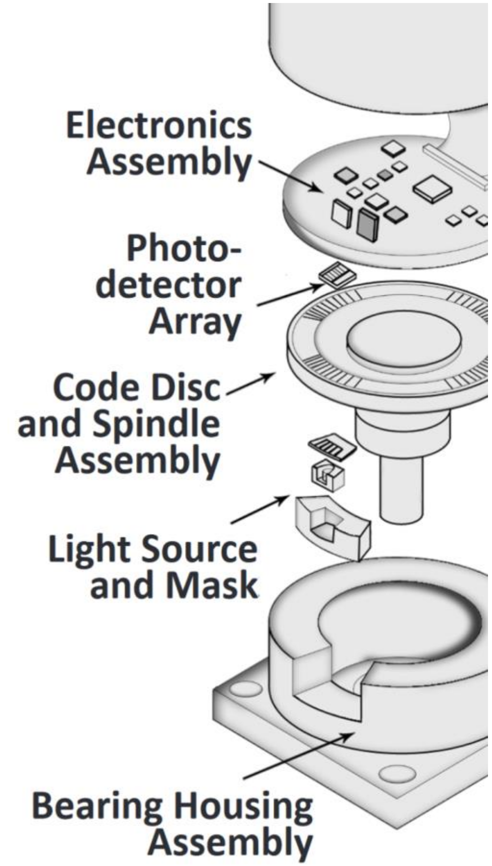
Inertial Measurement Units

- We learned about IMUs and accelerometers / gyroscopes
- IMUs report x, y, and z acceleration and x, y, z angular velocities
- This information can be fused to obtain global changes to position and orientation—proprietary algorithm within the IMU
    - We use this approach from our IMU, which provides position and orientation of the ball-bot
- Most IMUs can have their accel / velocity ranges scaled, depending on use
    - This provides optimal resolution when scaled correctly

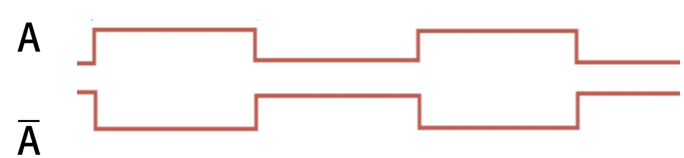


Optical Encoders

- We learned two types of encoders and quadrature decoding
- For optical encoders, a rotating disk inside encodes opaque lines or patterns
- When rotated, a photodetector senses the pulsing light
- This information is then converted and sent out as pulses for the motor driver
- Signals are often sent with the digital opposite, usually noted with a bar
  - Signals A and $\bar{A}$
- Pros: High resolution, resistant to magnetic interference, low cost
- Cons: Complex / fragile, larger size

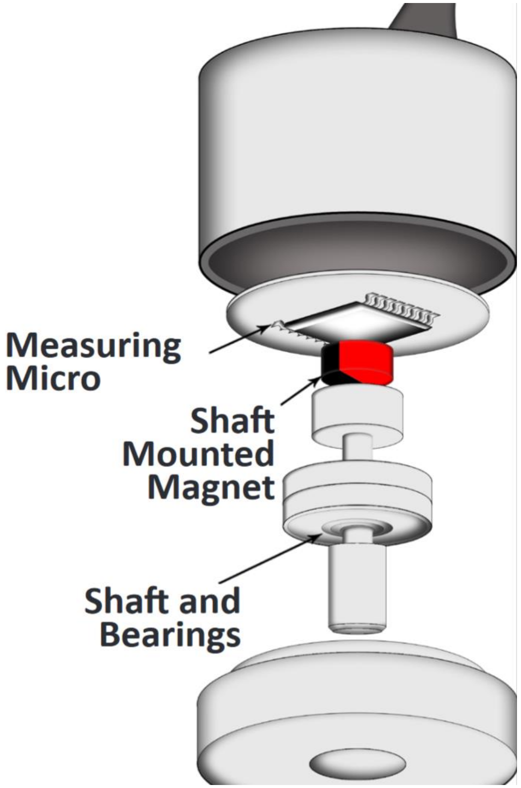


Example encoder signals—high voltage is usually 5V or 3.3V



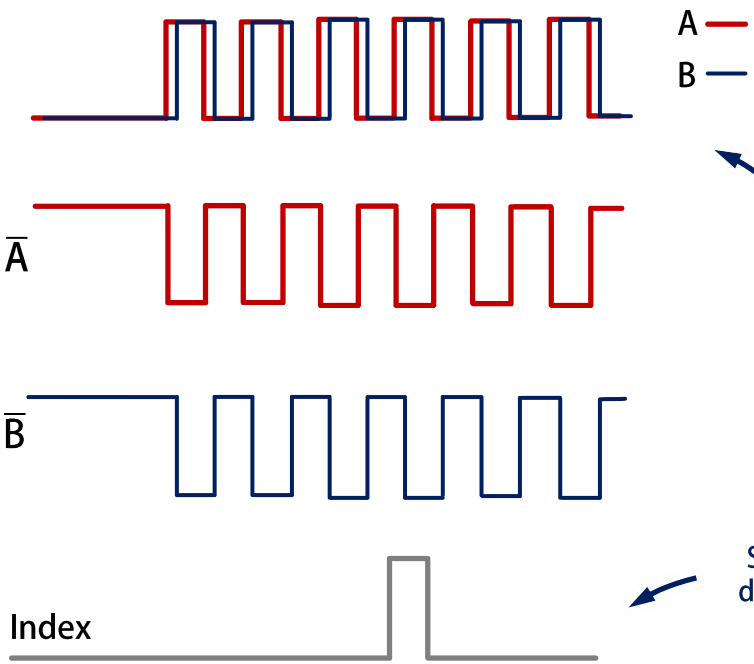
Magnetic Encoders

- Magnetic encoders use the change in local magnetic fields to sense rotation
- Typically based on the Hall-Effect, where a magnetic field across a plate creates a voltage
- Magnet is diametrically magnetized and at a specified location (~1-3 mm away from sensor)
- Outputs can have many forms (sine/cosine, digital, pulses)
- Pros: High resolution, absolute, low cost, simple
- Cons: ~susceptible to magnetic interference
- I use the AMS AS5048 encoder in my designs (link)



Quadrature Decoding (Relative)

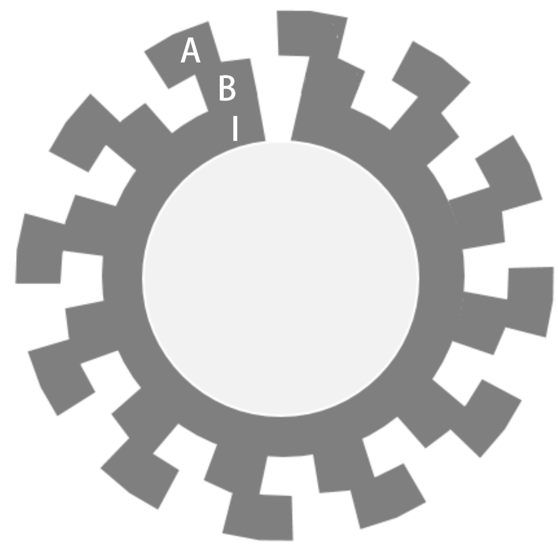
- Many motors use relative encoders, including ours!
  A key question is knowing the direction a motor is going
- This is accomplished using quadrature decoding: two encoders are positioned a small phase shift from each other
- The signal that rises first is used to know direction
- Indexing is used to know absolute position from a relative encoder



Which direction is this rotating?

Counterclockwise (if white is ON)

Some encoders don't have index marks

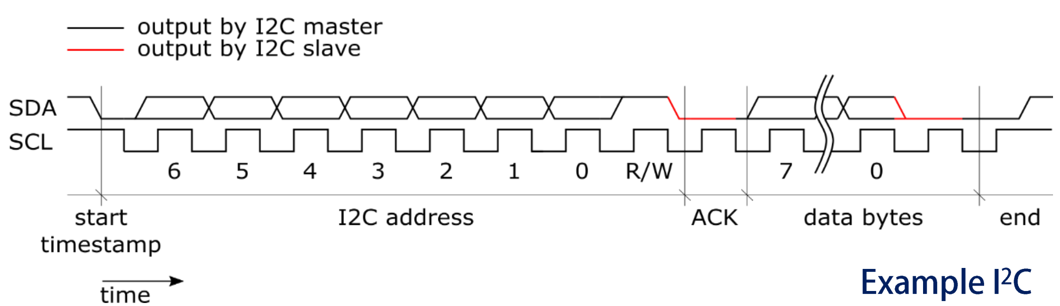


Digital Communication

- Digital communication is key to developing robots, and comes in many forms
  - Inter-Integrated Circuit bus (I^2C or I2C)
  - Serial Peripheral Interface (SPI or "spy")
  - Universal Serial Bus (USB)

We will discuss these

- Usually a data line and clock line that communicate information and timing
- Different sensors / chips on the bus need to know they are being communicated with – buses handle this differently
- We'll begin with look into I^2C as an example
  - 4 wires
  - SDA – data line
  - SCL – clock line
  - Power / ground
- Chips are defined by their I^2C address

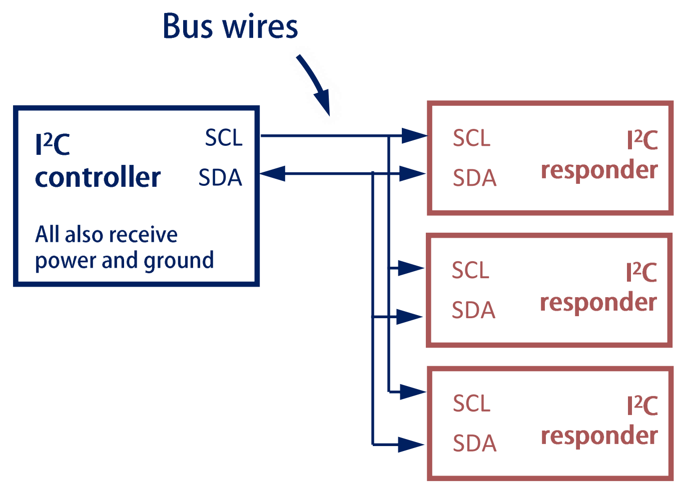


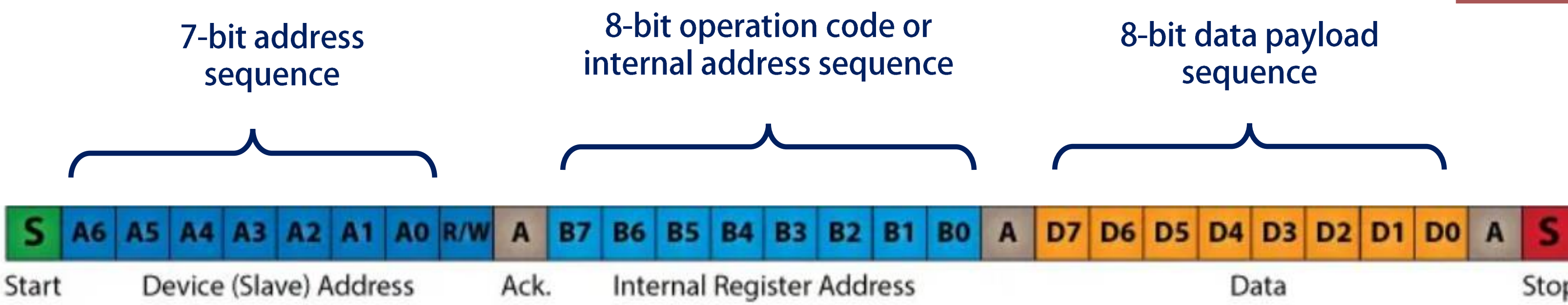
Example I^2C communication

I²C Communication

- Each sensor / chip on the I²C bus is assigned an address
- The address is usually set in hardware
  - Sometimes there are a few options
- The Controller or Master communicates with the Responders or Slaves
- This is defined in each message
- The address information and message structure is provided in the sensor datasheet

Sensors are addressed like a house on a street

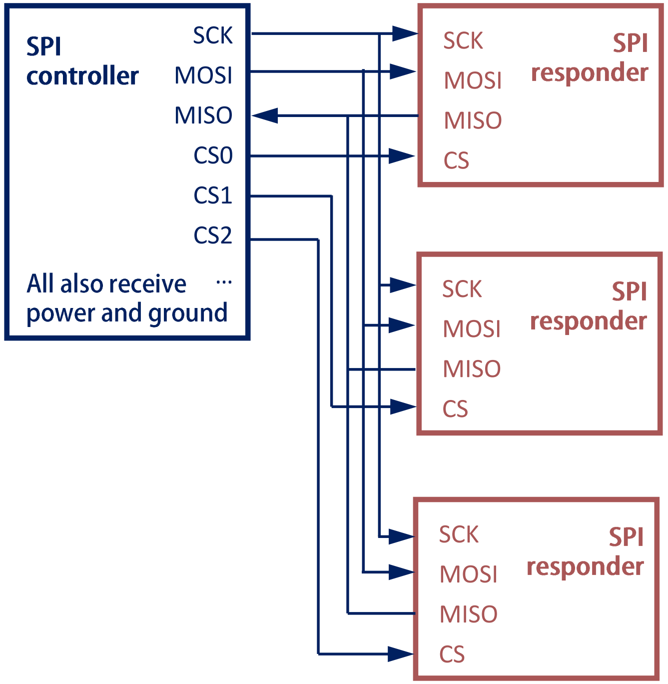




I²C / SPI Communication

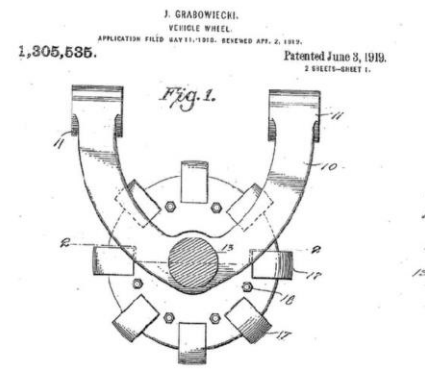
- I²C enables multiple controllers and multiple responders
- Speed is regulated by the clock line
- Half-duplex – only one sensor can communicate at a time
- Older and slower communication (typ. ~400 kB/sec)
- Mainly used for short distances—up to ~1 m unshielded

- **Serial Peripheral Interface (SPI)**
- 5+ wire bus (inc. power / ground)
- MISO – Data line – Master in, Slave out
- MOSI – Data line – Master out, Slave in
- SCK – clock line
- Slave select / Chip select – line for each chip
- Power / ground

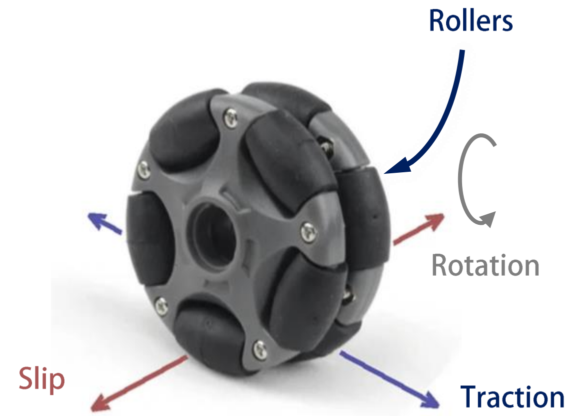


Omni Wheels

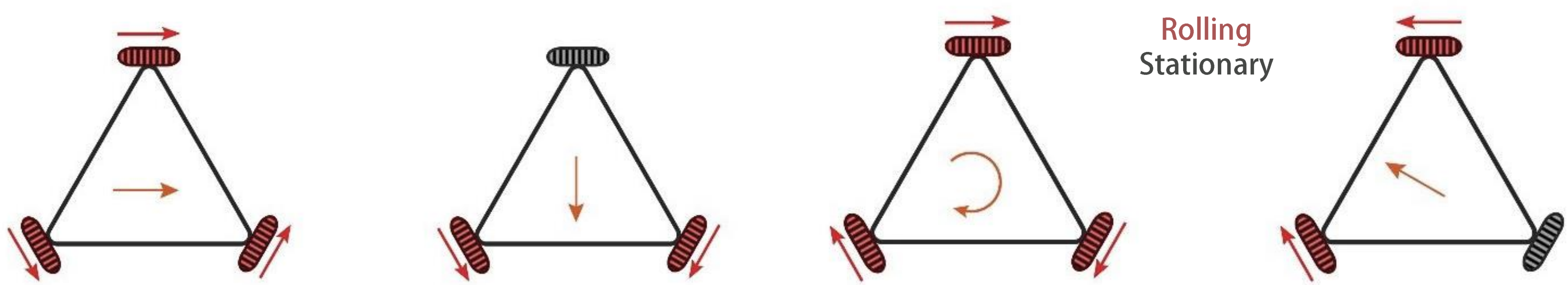
- Nontraditional rolling is provided by omni-wheels
- Small disks / rollers surround the circumference of an outer wheel
- Rollers roll perpendicular to the turning direction
- In some configurations, omni-wheels enable full specification of position and orientation of a robot (holonomic)
- Usually placed in an angled configuration
- Rolling contact on ball—slipping on inside roller
- Many sizes / shapes with different number of rollers / smoothness



J. Grabowiecki
USPTO 1919



Omni-wheel holonomic motion

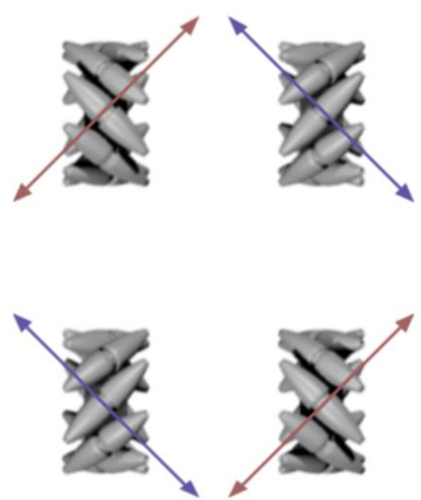


Mecanum Wheels

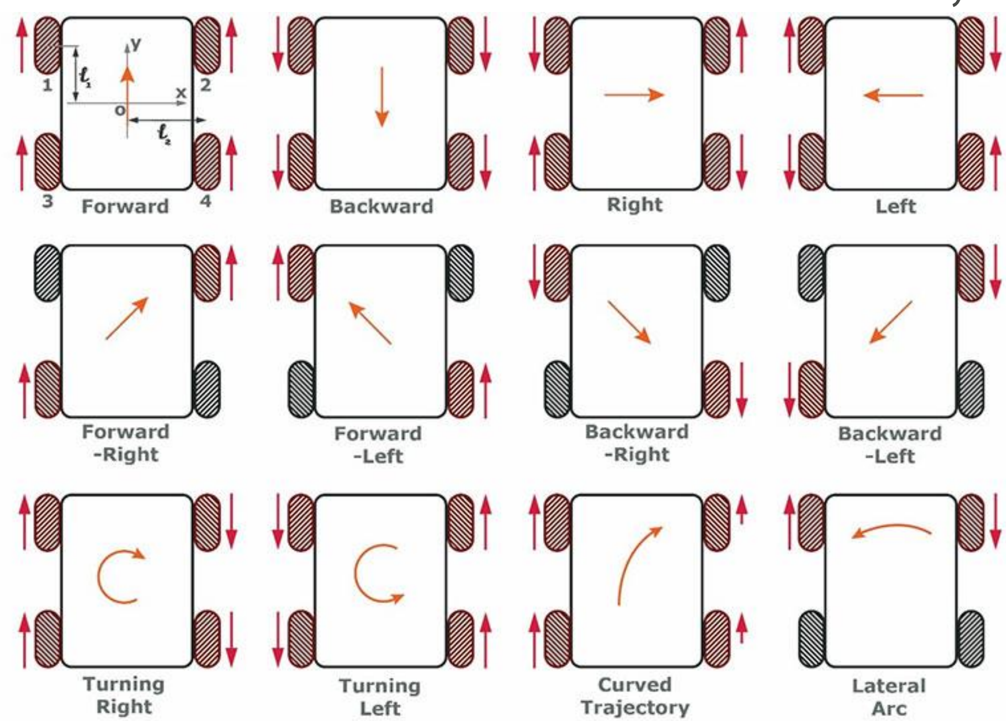
- Four wheeled systems can use mecanum wheels
- Enable holonomic motion
- They provide lateral motion with canted rollers
- Torque provides two known components of force

Example mecanum wheels

Force vectors caused by motor torque



Rolling
Stationary



Ball-bot Loop Architecture

- We discussed an overview of how the code runs on your ball-bot
- Our control loop iterates at 200 Hz due to IMU frequency limitations
- You were able to read from the IMU and encoders
  - The IMU will tell you rotation around the x and y axes
    - Units: Radians
  - The motor encoder will tell you the rotation of each motors
    - Units: Radians