Robot Drive System Fundamentals

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Ken Patton, Team 65 (Pontiac Northern + GM Powertrain)
Paul Copioli, Team 217 (Utica Schools + Ford/FANUC)

Robot Drive Systems

1. Drive System Requirements
2. Traction Fundamentals
3. FIRST Motors
4. Gearing Fundamentals
5. System Design Condition
6. Practical Considerations

Drive System Requirements
(Know what you want it to do!)

Before you start designing your machine, you must know what you want it to do

The game rules and your team's chosen strategy will help you decide what you want it to do

By spending some time and deciding for sure what you want it to do, you will be able to make good decisions about what design to choose

This needs to be a **team** effort

Some Features That Help Provide Good Drive System Attributes

Attribute	Good Features to Have
high top speed	high power, low losses, the right gear ratio
acceleration	high power, low inertia, low mass, the right gear ratio
pushing/pulling ability	high power, high traction, the right gear ratio, low losses
maneuverability	good turning method
accuracy	good control calibration, the right gear ratio
obstacle handling	ground clearance, obstacle "protection," drive wheels on floor
climbing ability	high traction, the right gear ratio, ground clearance
reliability/durability	simple, robust designs, good fastening systems
ease of control	intuitive control method, high reliability

TRACTION

Some Features That Help Provide Good Drive System Attributes

GEARING

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high top speed	high power, low losses, the right gear ratio
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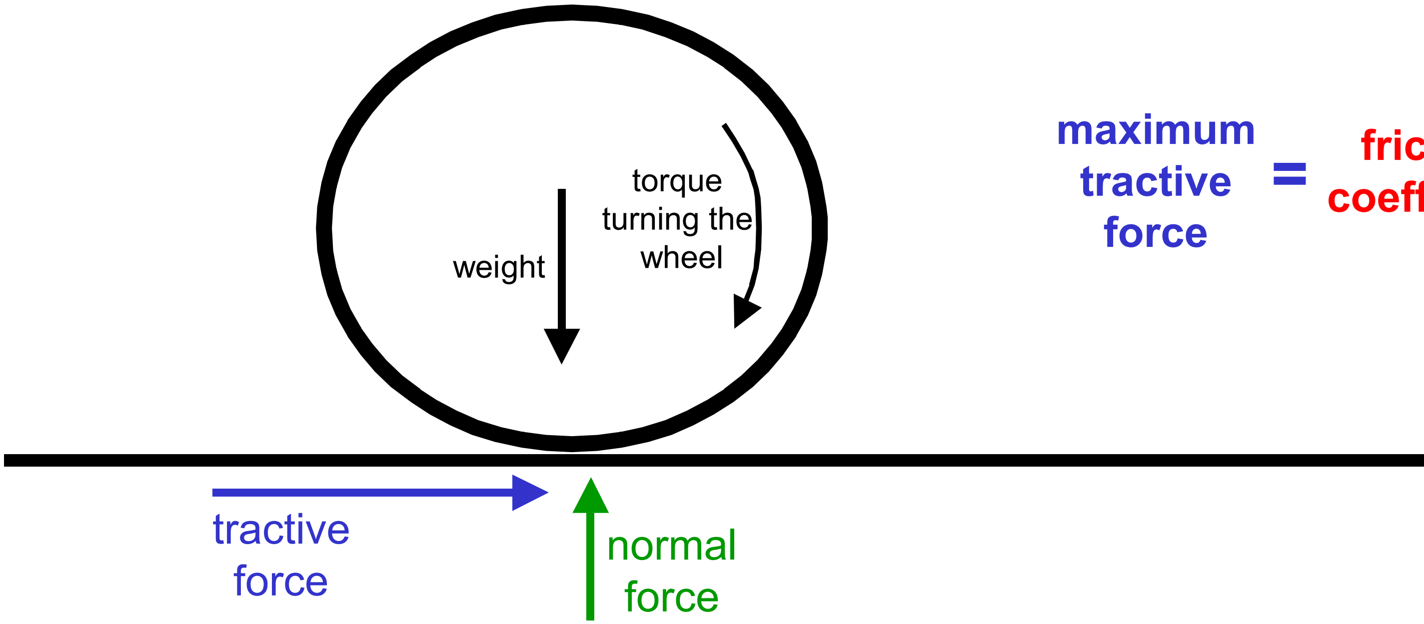
Traction Fundamentals Terminology



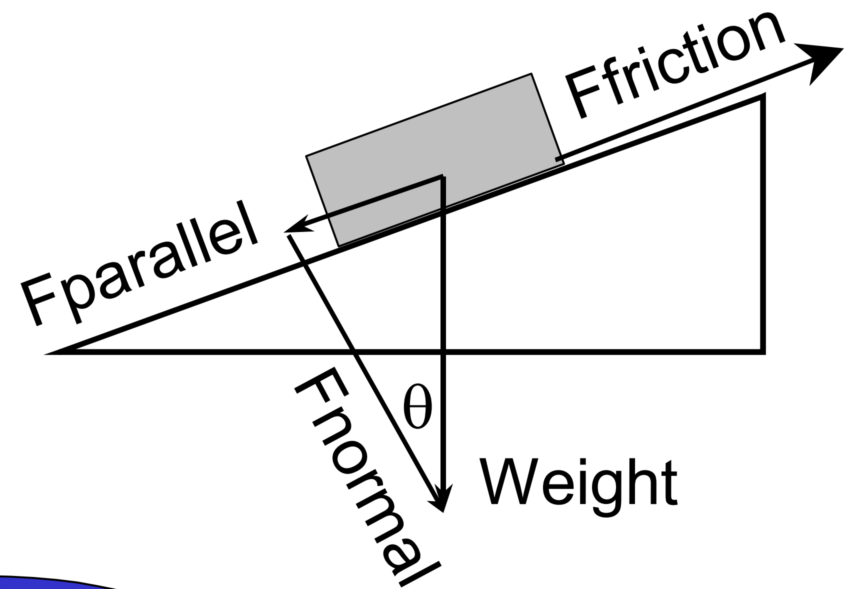
maximum tractive force = **friction coefficient** x **normal force**

The friction coefficient for any given contact with the floor, multiplied by the normal force, equals the maximum tractive force can be applied at the contact area.

Tractive force is important! It's what moves the robot.

Traction Fundamentals
The Basic Equations

- $F_{friction} = \mu * F_{normal}$
- Experimentally determine μ:
- $F_{normal} = Weight * \cos(\theta)$
- $F_{parallel} = Weight * \sin(\theta)$



When $F_{friction} = F_{parallel}$, no slip

$F_{friction} = \mu * Weight * \cos(\theta)$

$F_{parallel} = Weight * \sin(\theta) = \mu * Weight * \cos(\theta)$

$\mu = \sin(\theta) / \cos(\theta)$ → $\mu = \tan(\theta)$

Traction Fundamentals "Friction Coefficient"

Friction coefficient is dependent on:

- Materials of the robot wheels (or belts)
- Shape of the robot wheels (or belts)
- Material of the floor surface
- Surface conditions

Traction Fundamentals
Wheel Materials

Friction coefficient is dependent on:

Materials of the robot wheels (or belts) →

Shape of the robot wheels (or belts)

Material of the floor surface

Surface conditions

High Friction Coeff:
soft materials
"spongy" materials
"sticky" materials

Low Friction Coeff:
hard materials
smooth materials
shiny materials

It is often the case that "good" materials wear out much faster than "bad" materials - don't pick a material that is TOO good!

Advice: make sure you have tried & true LEGAL material

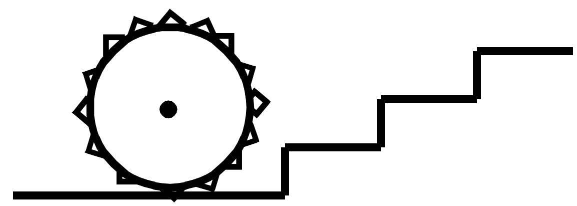
Traction Fundamentals
Shape of Wheels (or Belts)

Friction coefficient is dependent on:

- Materials of the robot wheels (or belts)
- **Shape of the robot wheels (or belts)**
- Material of the floor surface
- Surface conditions

Want the wheel (or belt) surface to "interlock" with the floor surface

On a large scale:

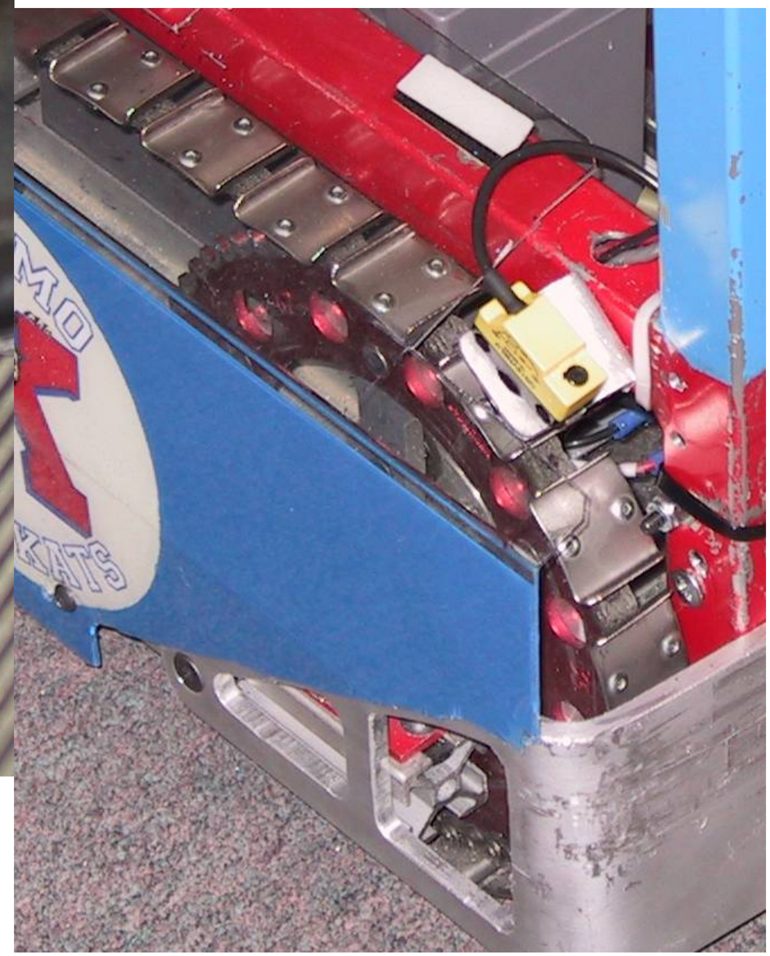


And on a small scale:

(see previous slide)

WANTED!

for breaking the rules



Traction Fundamentals
Material of Floor Surface

Friction coefficient is dependent on:

- Materials of the robot wheels (or belts)
- Shape of the robot wheels (or belts)
- **Material of the floor surface** →
- Surface conditions

This is not up to you!

Know what surfaces (all of them) that you will be running on.

Traction Fundamentals
Surface Conditions

Friction coefficient is dependent on:

- Materials of the robot wheels (or belts)
- Shape of the robot wheels (or belts)
- Material of the floor surface
- **Surface conditions**

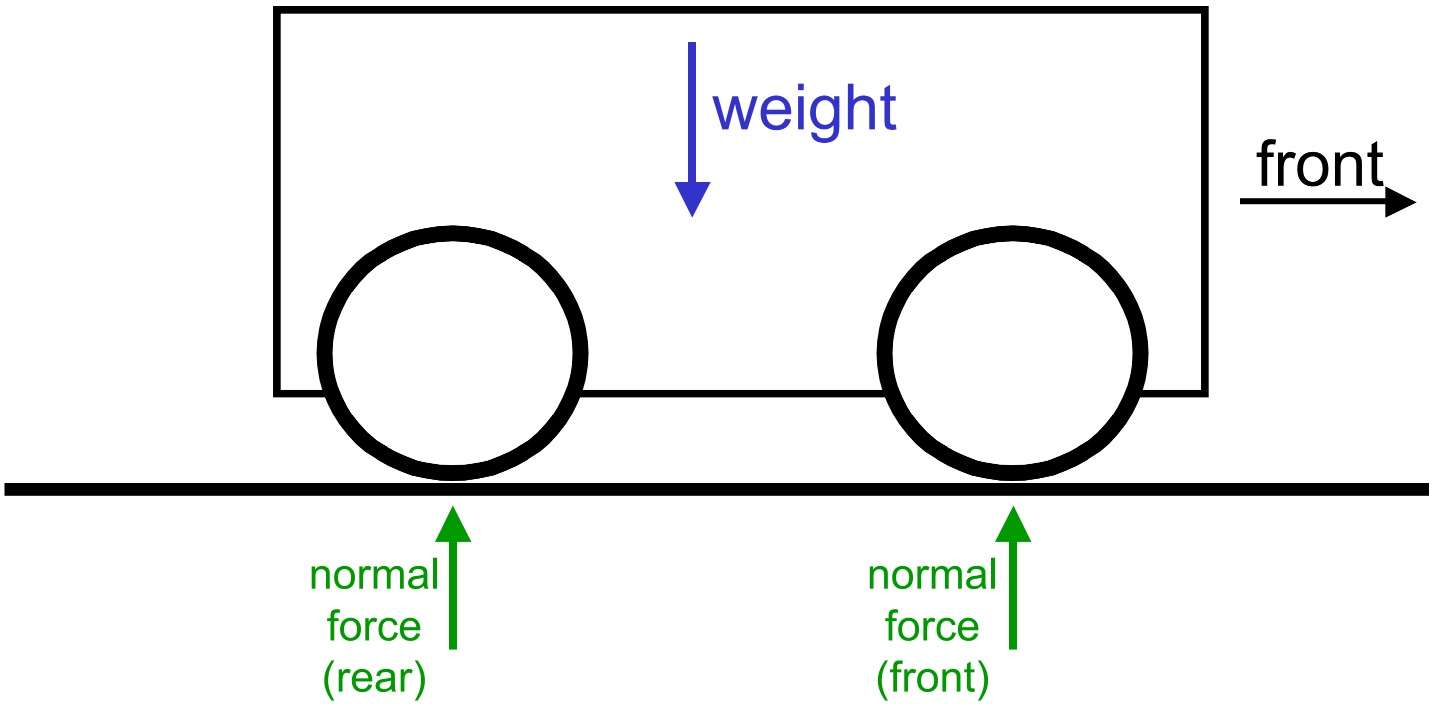
In some cases this will be up to you.

Good:
clean surfaces
"tacky" surfaces

Bad:
dirty surfaces
oily surfaces

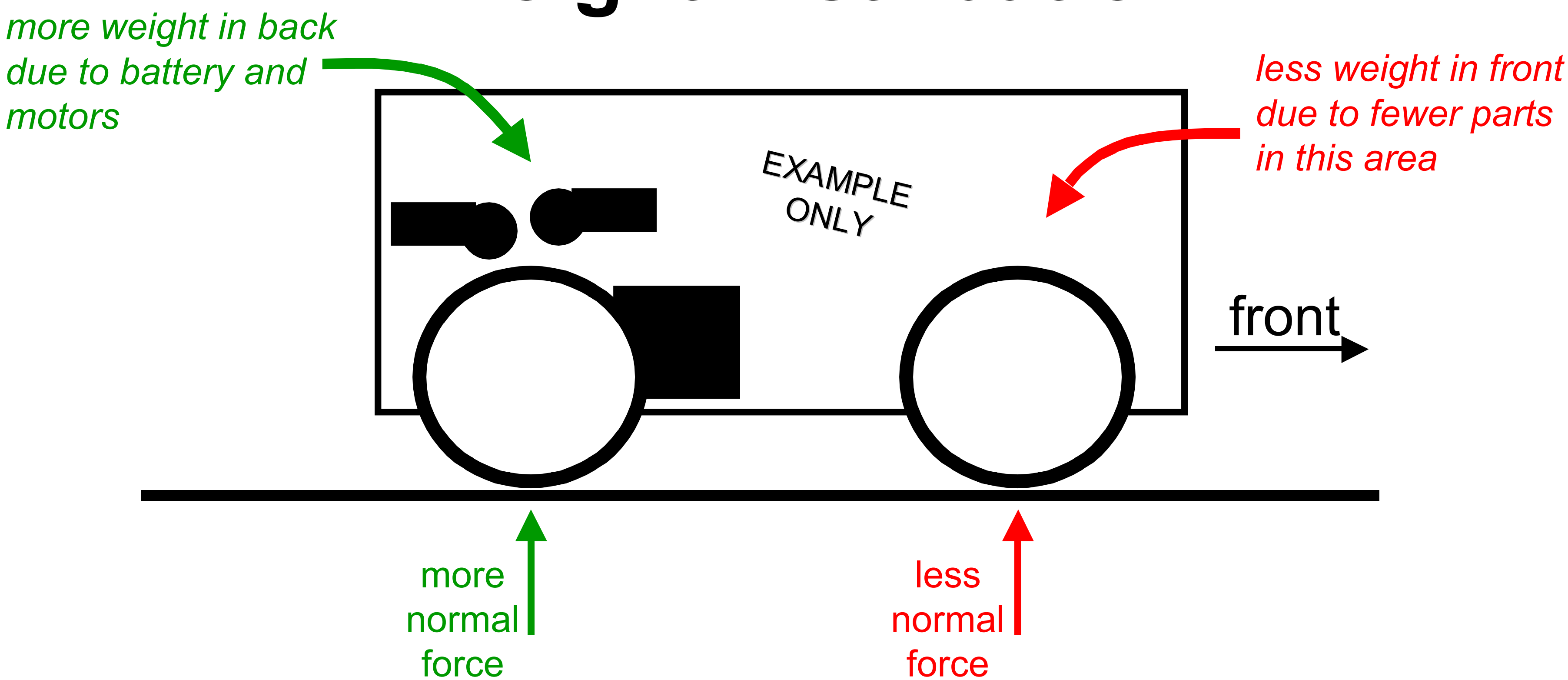
Don't be too dependent on the surface condition, since you cannot always control it. But … don't forget to clean your wheels.

Traction Fundamentals "Normal Force"



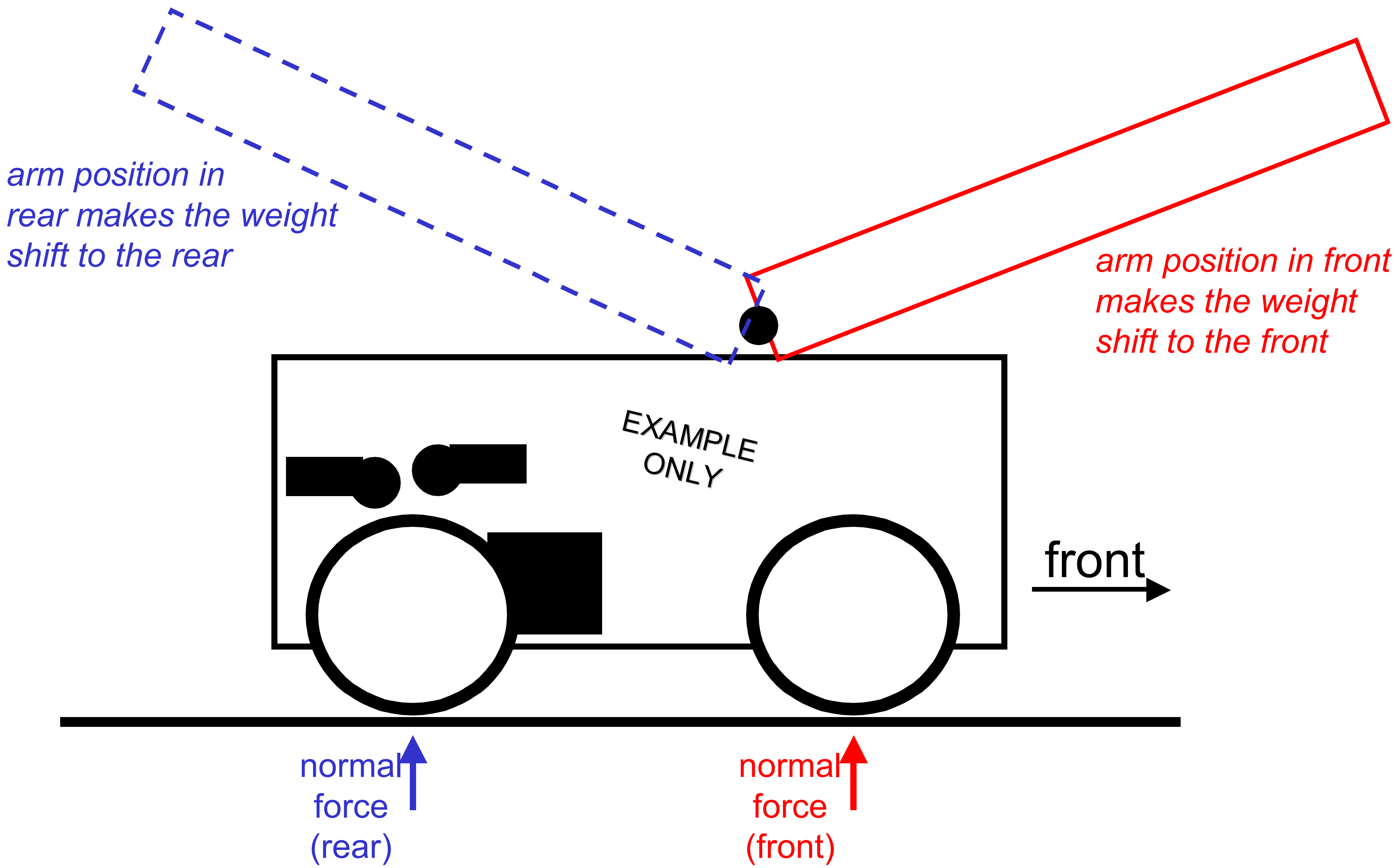
The normal force is the force that the wheels exert on the floor, and is equal and opposite to the force the floor exerts on the wheels. In the simplest case, this is dependent on the weight of the robot. The normal force is divided among the robot features in contact with the ground.

Traction Fundamentals
"Weight Distribution"



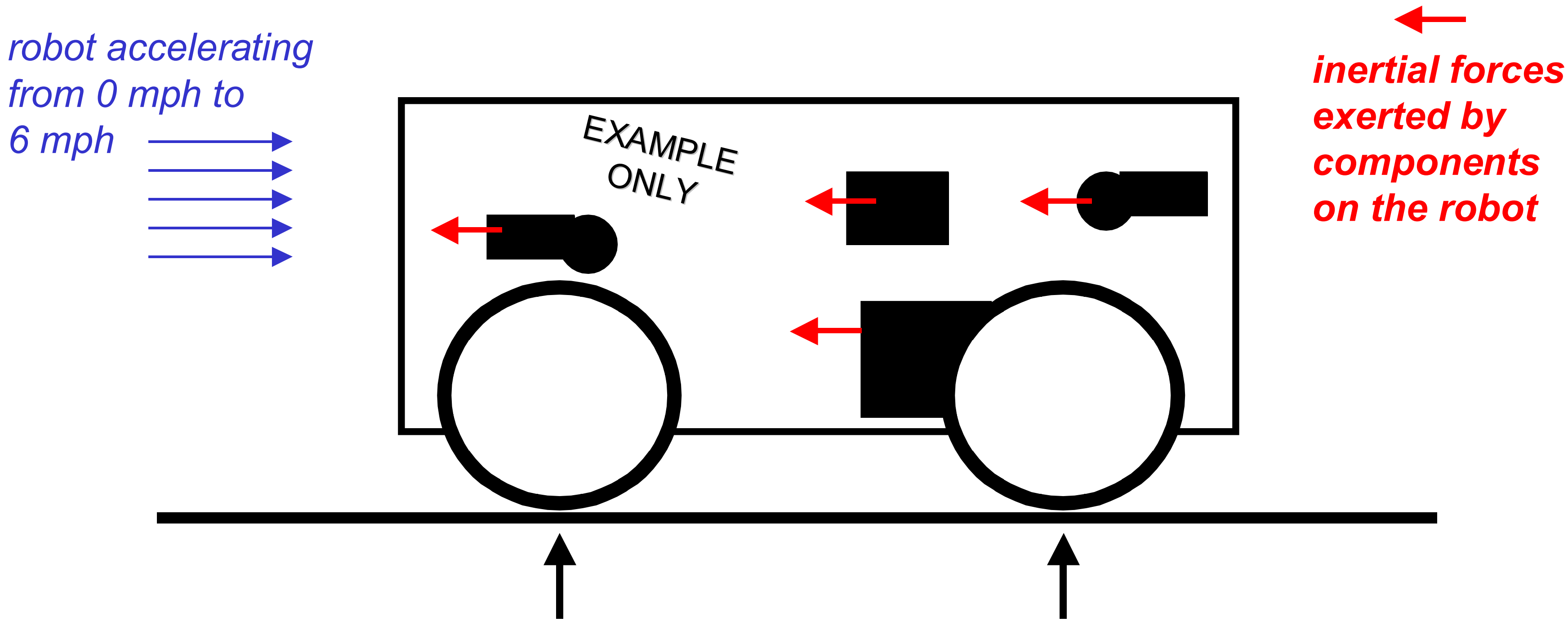
The weight of the robot is **not** equally distributed among all the contacts with the floor. Weight distribution is dependent on where the parts are in the robot. This affects the normal force at each wheel.

Traction Fundamentals
Weight Distribution is Not Constant



"Enhanced" Traction

Traction Fundamentals
"Weight Transfer"



more normal force *is exerted on the rear wheels because inertial forces tend to rotate the robot toward the rear*

less normal force *is exerted on the front wheels because inertial forces tend to rotate the robot away from the front*

In an extreme case (with rear wheel drive), you pull a wheelie
In a really extreme case (with rear wheel drive), you tip over!

Traction Fundamentals
Consider “Transient” Conditions

transient = changing with time

What happens when the robot bumps into something?

What happens when the robot picks up an object?

What happens when the robot accelerates hard?

What things can cause the robot to lose traction?

Traction Fundamentals
Number & Location of Drive Wheels

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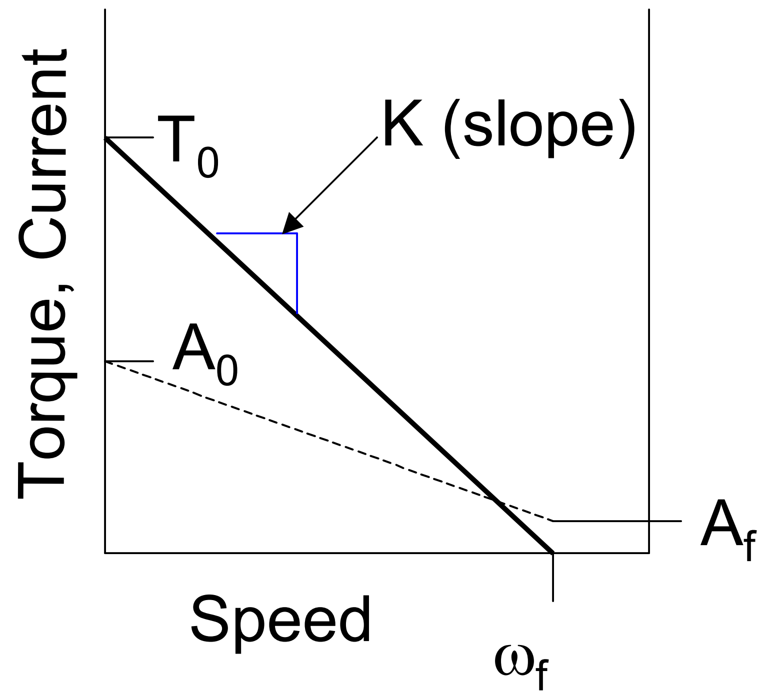
FIRST Motors

1. Motor Characteristics (Motor Curve)
2. Max Power vs. Power at 40 Amps
3. Motor Comparisons
4. Combining Motors

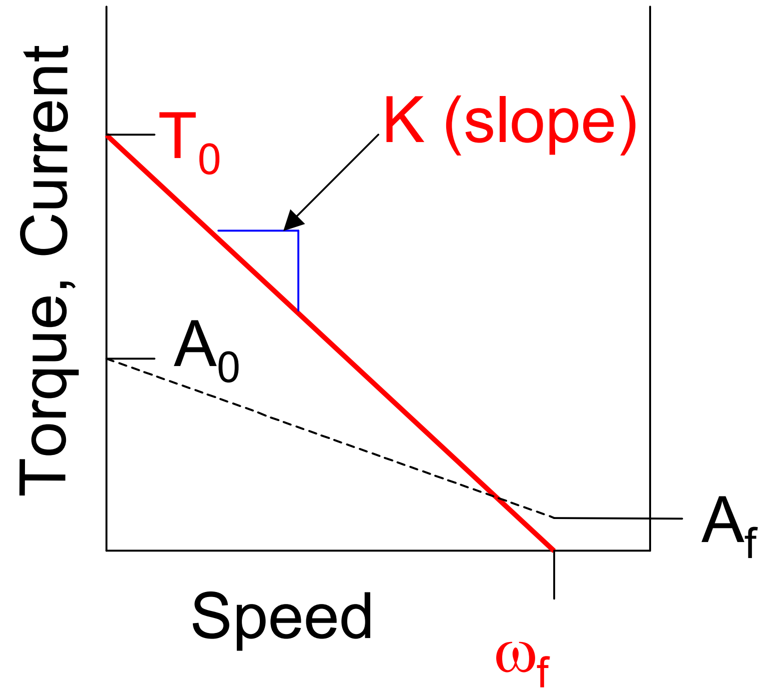
Motor Characteristics

- Torque v Speed Curves
  - Stall Torque (T_0)
  - Stall Current (A_0)
  - Free Speed (ω_f)
  - Free Current (A_f)



Slope-Intercept (Y=mX + b)

- Y=Motor Torque
- m=K (discuss later)
- X=Motor Speed
- b=Stall Torque (T_0)



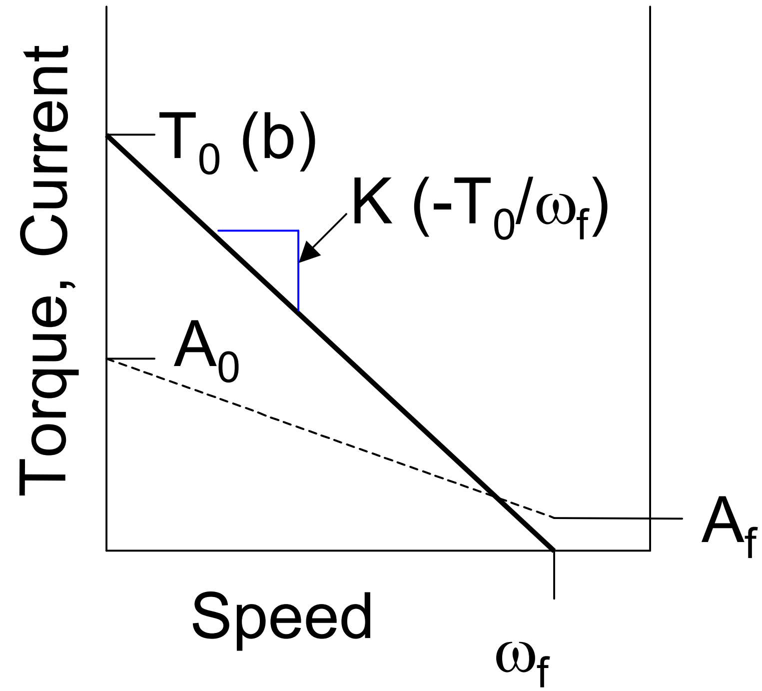
What is K? … It is the slope of the line.

Slope = change in Y / change in X = $(0 - T_0)/(\omega_f - 0) = -T_0/\omega_f$

K = Slope = $-T_0/\omega_f$

(Y=mX + b) Continued ...

- Y=Motor Torque
- $m = K = -T_0/\omega_f$
- X=Motor Speed
- b=Stall Torque = T_0

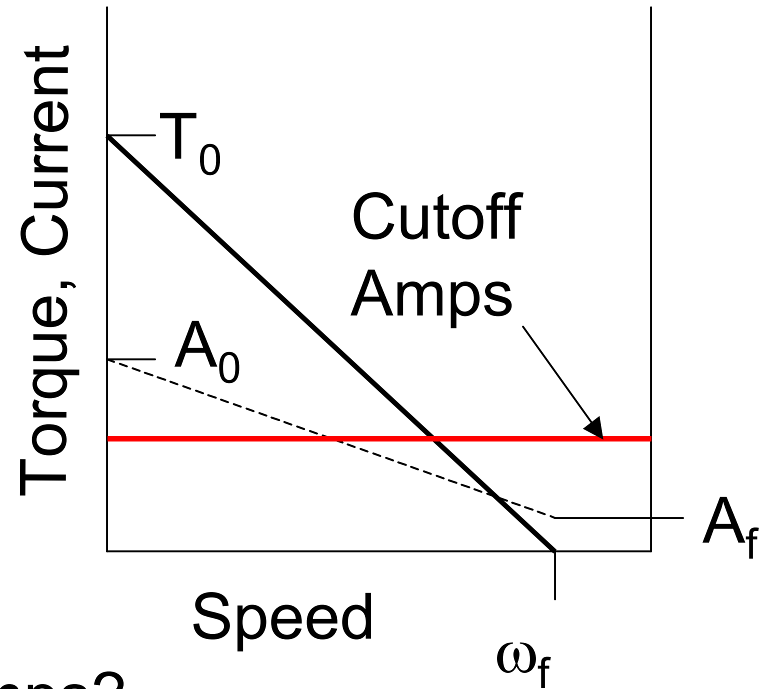


Equation for a motor:

Torque = $(-T_0/\omega_f)$ * Speed + T_0

Current (Amps) and FIRST

- What are cutoff Amps?
  - Max useable amps
  - Limited by breakers
  - Need to make assumptions



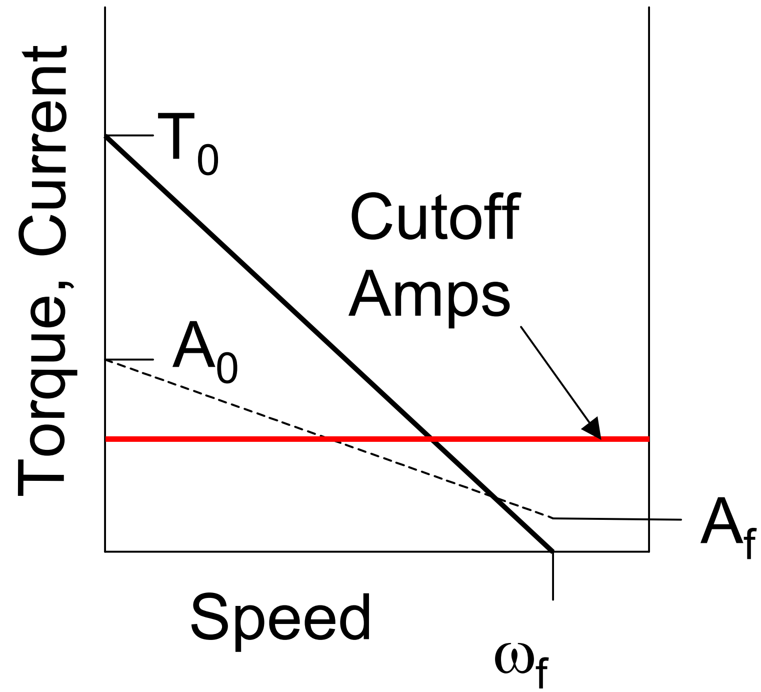
Can our Motors operate above 40 amps?

- Absolutely, but not continuous.

When designing, you want to be able to perform continuously; so finding motor info at 40 amps could prove to be useful.

Torque at Amp Limit

- T_{40} = Torque at 40 Amps
- ω_{40} = Speed at 40 Amps



Current Equation:

Current = $(A_f - A_0)/\omega_f$ * Speed + A_0

Motor Equation:

Torque = $(-T_0/\omega_f)$ * Speed + T_0

Power - Max vs. 40 Amps

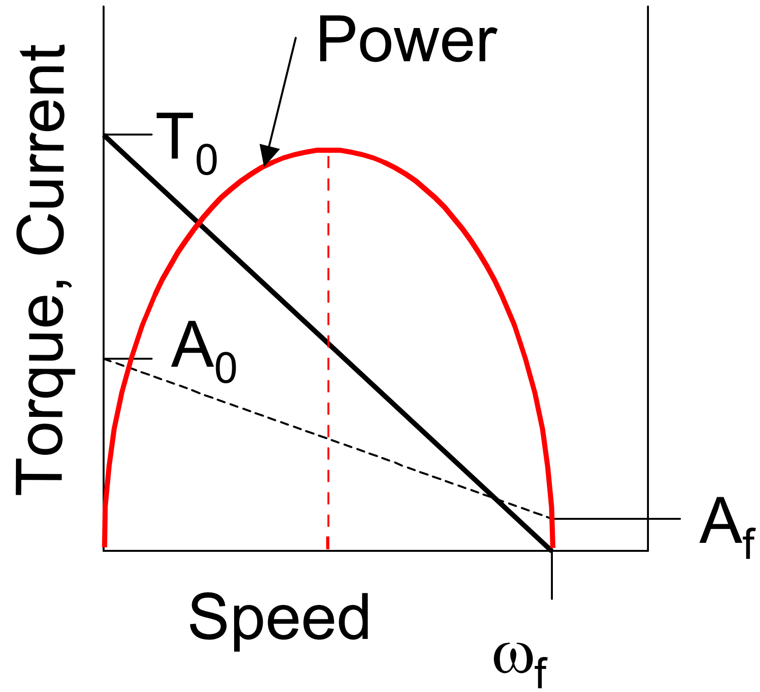
Power = Torque * Speed

Must give up torque for speed

Max Power occurs when:

$T = T_0/2$ & $\omega = \omega_f/2$

What if max power occurs at a current higher than 40A?



Paul's Tip #1: Design drive motor max power for 40A!

Power is Absolute - It determines the Torque Speed tradeoff!

Motor Comparisons

Let's Look at Some FIRST Motors

- Chiaphua Motor
- Fisher-Price Motor

We will compare T_0, ω_f, A_0, A_f, T_{40}, ω_{40}, max power (P_{max}), amps @ max power (A_{pmax}), and power at 40 amps (P_{40}).

Motor Comparisons

Motor	T0	Wf	A0	Af	Pmax	T40	W40	P40
	N-m	RPM	Amps	Amps	Watts	N-m	RPM	Watts
CIM	2.45	5,342	114	2.4	342.6	0.80	3,647	305.5
Mabuchi F.P.	0.642	24,000	148	1.5	403.4	0.18	17,500	322.5

Motor Equations:

1. 2006 Fisher-Price: $T = (-0.64/24{,}000) * \omega + 0.64$
2. 2002-07 Chiaphua: $T = (-2.45/5{,}342) * \omega + 2.45$

Combining Motors

Using multiple motors is common for drive trains. We will look at matching the CIM and the Fisher-Price.

I try to match at free speed, but you can match at any speed you like!!

ω_f FP / ω_f Chiaphua = 24,000/5342 ~ 9/2 = Gear Ratio

We will use an efficiency of 95% for the match gears.

More to come on Gear Ratio & Efficiency a little later!

Combined Motor Data

Motor	T0 N-m	Wf RPM	Pmax Watts	T40 N-m	W40 RPM	P40 Watts
F-P & CIM	5.19	5,337	725	1.7	3,642	648
CIM & CIM	4.9	5,342	685	1.6	3,647	611
CIM, CIM, & F-P	7.64	5,339	1068	2.63	3,644	1004

Motor Equations:

1. F-P & CIM: $T = (-5.19/5{,}337) * \omega + 5.19$
2. CIM & CIM: $T = (-4.9/5{,}342) * \omega + 4.9$
3. CIM, CIM, & F-P: $T = (-7.64/5{,}339) * \omega + 7.64$

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Gearing Fundamentals "Torque" and "Power"

(some oversimplified definitions)

Torque is the ability to exert a rotational effort. In this case, the ability to make a wheel turn.

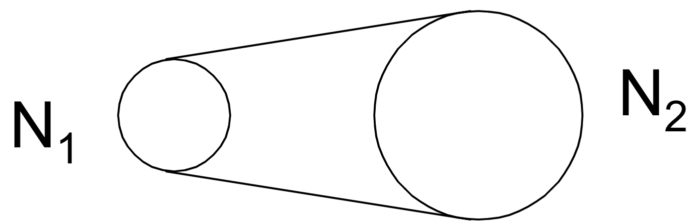
Torque determines whether or not you can get the job done.

Power is the rate at which energy is delivered. In this case, the rate at which wheel torque is being transferred to the floor.

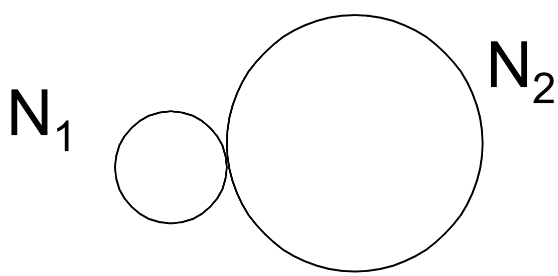
Power determines how fast you can get the job done.

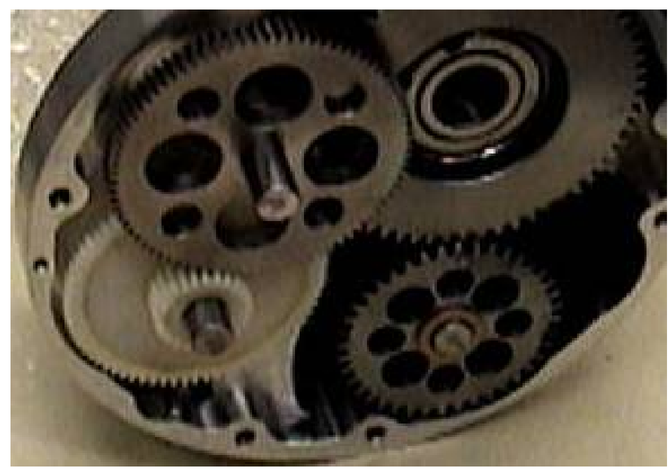
Types of Drive Mechanisms

1. Chain & Belt
   Efficiency ~ 95% - 98%
   $GR = N_2/N_1$



2. Spur Gears
   Efficiency ~ 95% - 98%
   $GR = N_2/N_1$



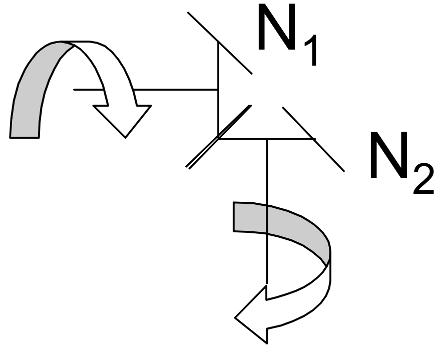


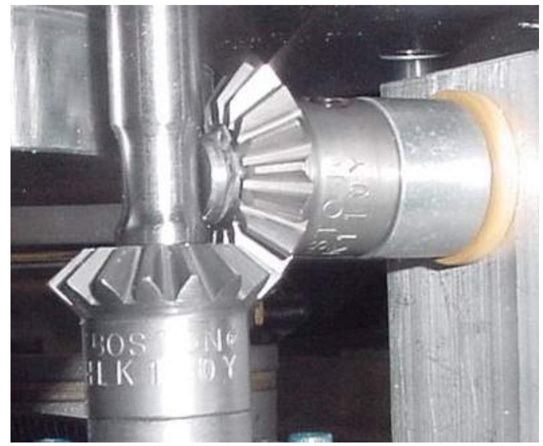
Types of Drive Mechanisms

3. Bevel Gears

   Efficiency ~ 90% - 95%

   GR = N_2/N_1



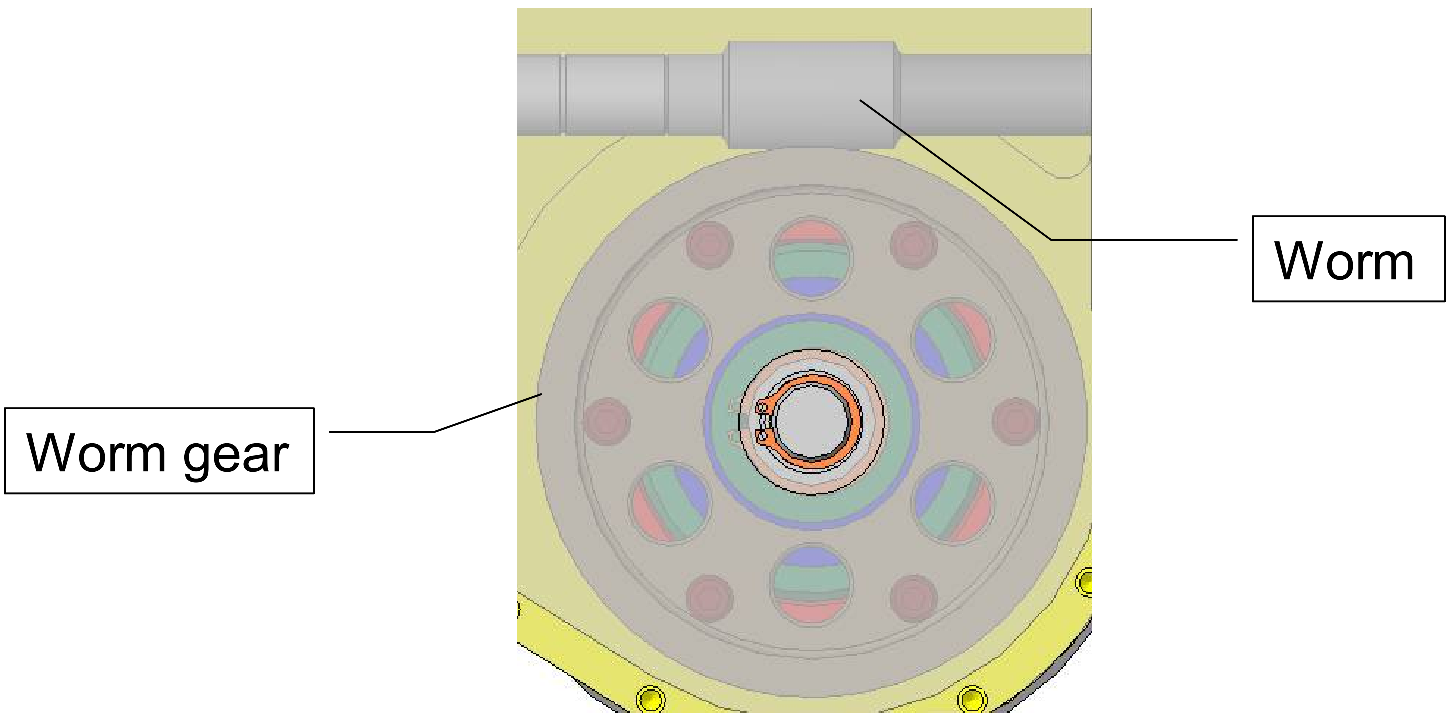


Types of Drive Mechanisms

4. Worm Gears

Efficiency ~ 40% - 70%

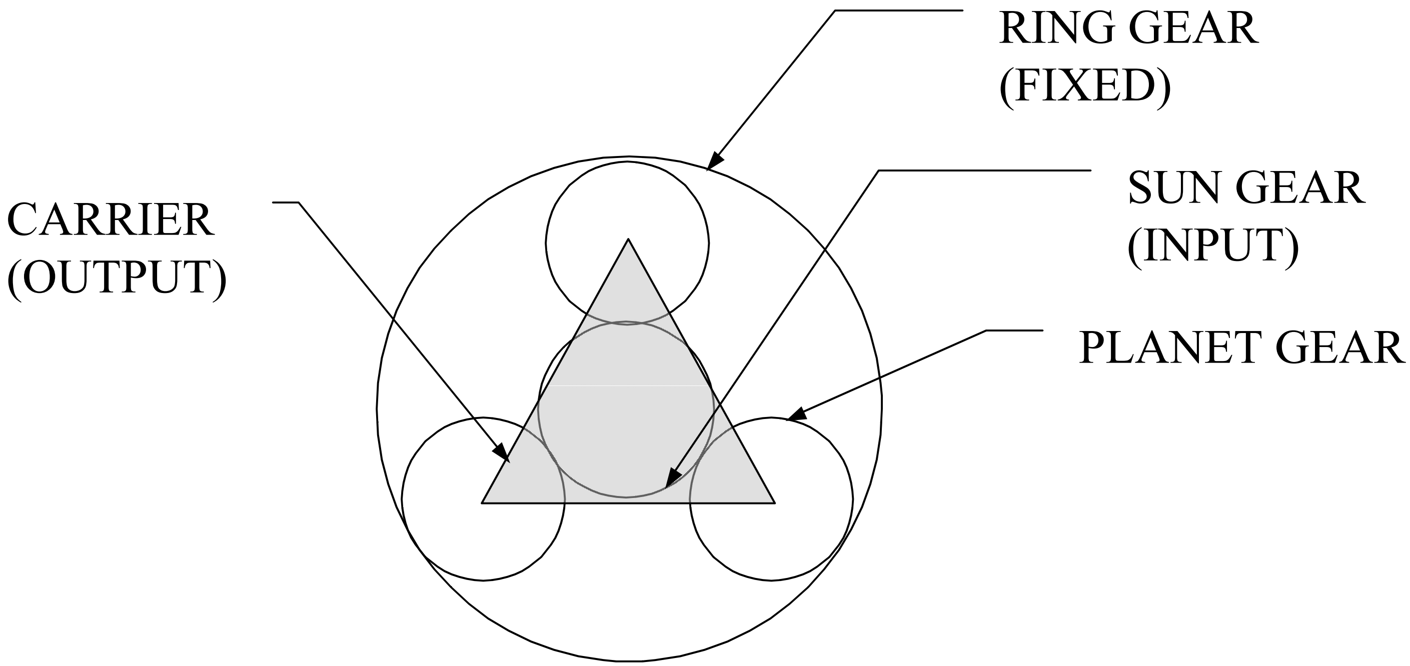
$$GR = \frac{\text{\# Teeth on Worm Gear}}{\text{\# of Threads on worm}}$$



Types of Drive Mechanisms

5. Planetary Gears

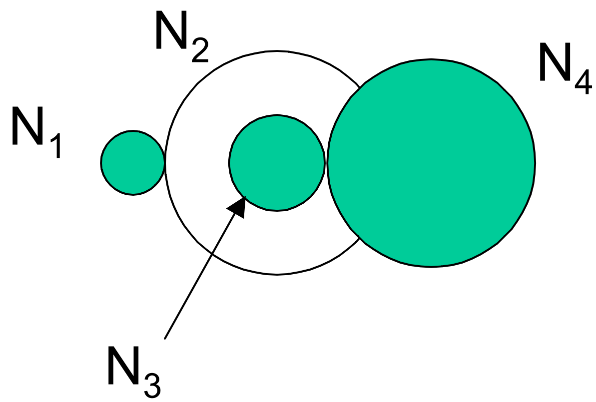
Efficiency ~ 80% - 90%



$$GR = \frac{N_{ring}}{N_{sun}} + 1$$

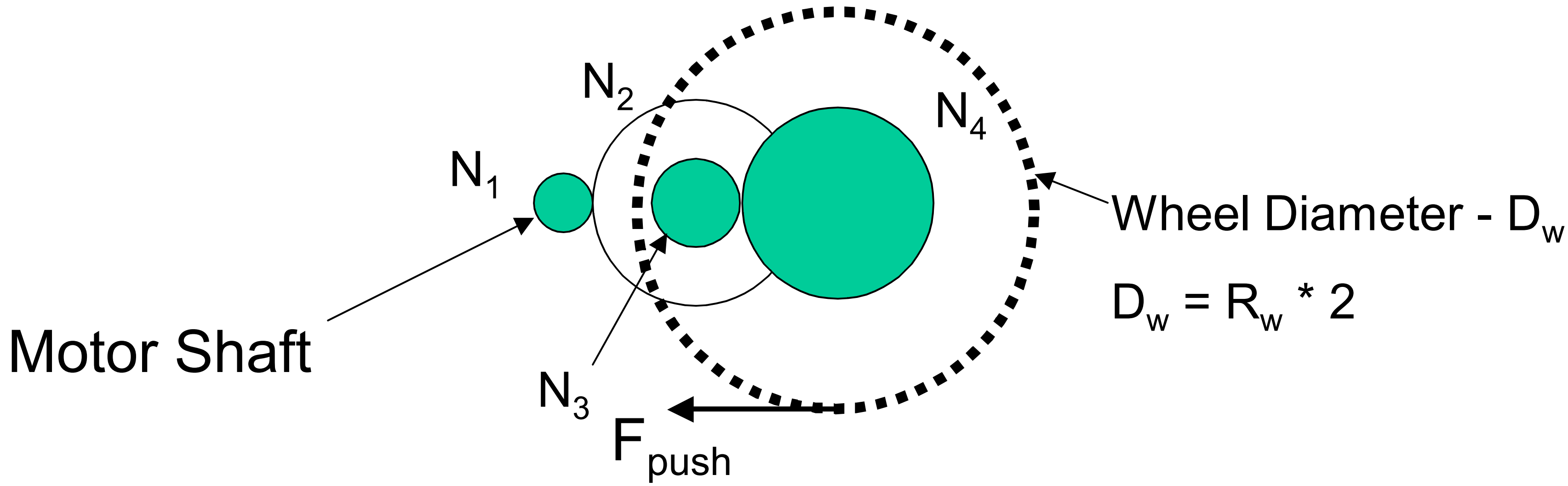
Gearing Basics

- Consecutive gear stages multiply:



- Gear Ratio is $(N_2/N_1) * (N_4/N_3)$
- Efficiency is .95 *.95 = .90

Gearing Basics - Wheel Attachment



- Gear 4 is attached to the wheel
- Remember that $T = F * R_w$
- Also, $V = \omega * R_w$
- $T_4 = T_1 * N_2/N_1 * N_4/N_3 * .95 * .95$
- $\omega_4 = \omega_1 * N_1/N_2 * N_3/N_4$
- $F = T_4 / R_w$
- $V = \omega_4 * R_w$

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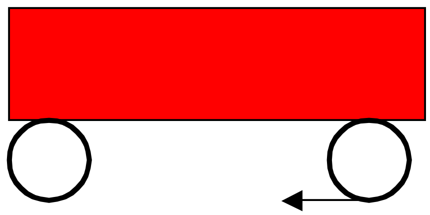
Design Condition



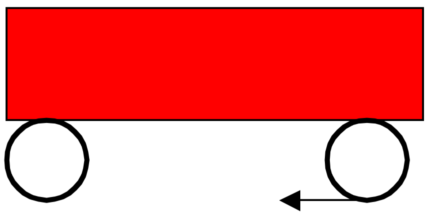
- Assumptions
  - 4 wheel drive, 4 motors.
  - Weight is evenly distributed.
  - Using all spur gears.
- Terms
  - W = Weight of robot
  - W_t = Weight transferred to robot from goals
  - T_{out} = wheel output Torque
- Find the gear ratio & wheel diameter to maximize push force.

The maximum force at each wheel we can attain is ???

$F_{max} = F_{friction} = \mu * (W + W_t)$ {on a flat surface}

Now $T = F * R_w$ ----> $F = T_{out} / R_w$

Design Condition Continued



- $T_{out} = T_{40} * GR * eff$

$F_{friction} = T_{out} / R_w$: $\mu * (W + W_t) = T_{40} * GR * eff / R_w$

$$GR/R_w = \frac{\mu * (W + W_t)}{T_{40} * eff}$$

The above gives you the best combination of gear ratio and wheel diameter for maximum pushing force!

Design Condition Continued

O.K. So what is my top speed?

$$V_{max}\,[\text{m/sec}] = \frac{0.9 * \omega_{free} * \pi * 2 * R_w}{60 * GR}$$

Where ω_{free} is in RPM, R_w is in meters.

The 0.9 accounts for drive friction slowing the robot down.

Design Condition Applied to Kit Transmission Design

Given (constraints):

- $W = 130$ lb
- $W_t = 0$ lb
- $\mu = 0.8$
- eff = 0.86
- $T_{40} = 2 * 1.18$ ft-lb
- $R_w = 4$ in

$$GR/R_w = \frac{0.8 * (130 + 0)}{2 * 1.18 * 0.86}$$

$GR = 17$

*Actual kit gear ratio is 50/14 * 50/14 * 28/21 = 17*

Design Condition Applied to Kit Transmission Design

O.K. So what is my top speed and pushing force?

$$V_{max}\ [ft/sec] = \frac{0.9 * 5342 * \pi * 2 * 4/12}{60 * 17} = 10\ ft/sec$$

$$Fmax\ [lb] = \frac{2 * 1.18 * 17 * 0.86}{4/12} = 103.5\ lb$$

close enough!

$$F_{max}\ \text{available} = 0.8 * (130 + 0) = 104\ lb$$

Gearing Fundamentals
Robot Drive System Simulation

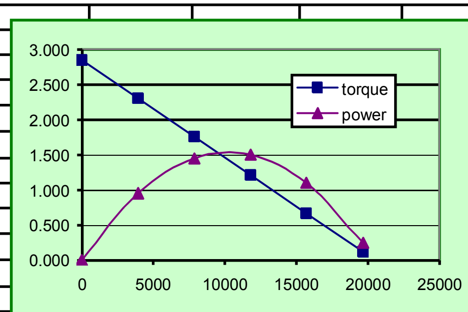
12/25/2003 FIRST DRIVE SYSTEM SIMULATOR v3
USE AT YOUR OWN RISK, NO WARRANTY IMPLIED
KEN PATTON GM POWERTRAIN TEAM 65

GEAR RATIO INPUT DATA

60	gearbox ratio (drill motor speed : output speed)
15	drive sprocket # of teeth
15	driven sprocket # of teeth

GEARBOX CONSTANTS

0.900	gearbox efficiency (not rest of driveline)
0.2	gearbox spin loss at output side (Nm)



This motor curve is used, based on the inputs in the motors spreadsheet.

Nmotor (rpm)	Nmotor (rad/s)	Tmotor (Nm)	Pmotor (kW)	current (A)
0	0	2.850	0.000	468
3934	412	2.304	0.949	376
7868	824	1.757	1.448	285
11802	1236	1.211	1.496	193
15736	1648	0.664	1.094	101
19670	2060	0.118	0.242	10

ROBOT INPUT DATA

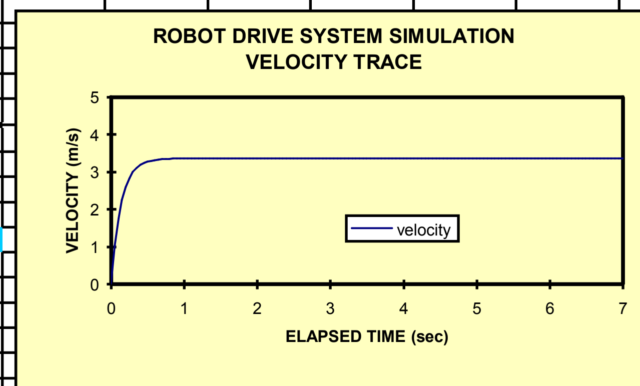
0.1016	drive wheel radius (m)	12.25	Fstatic (N)	0.000156	I @motor	0.05	timestep
58.98367	mass of robot (kg)	0.95	ndriveline	0.005	I @wheels		
		0.93	ntires				

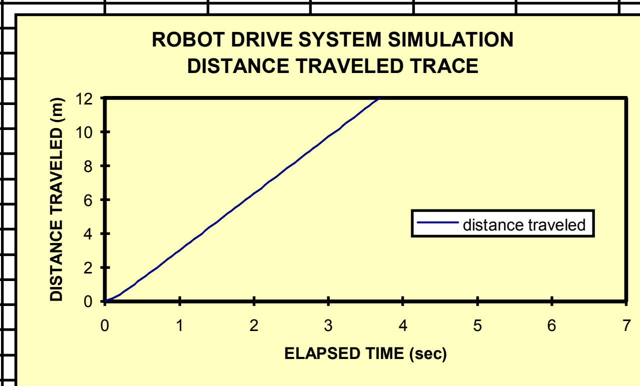
EFFIC CONSTANTS

time (sec)	robot v (m/s)	robot v (mph)	distance traveled (m)	Ngb,out (rpm)	*all motors* Tgb,out (Nm)	robot dv/dt (m/s^2)	robot dv/dt (g)	*Approx* Current (A)	Nmotor (rpm)	Fpush (N)
0	0.000	0.00							0	1221.8
0.05	1.036	2.32							5841	844.0
0.1	1.751	3.92							9875	583.0
0.15	2.245	5.02							12662	402.7
0.2	2.587	5.79							14588	278.2
0.25	2.823	6.31							15918	192.2
0.3	2.986	6.68							16836	132.8
0.35	3.098	6.93							17471	91.7
0.4	3.176	7.10	0.985	298	8.76	1.074	0.110	27.2	17909	63.4
0.45	3.229	7.22	1.147	304	6.48	0.742	0.076	20.1	18212	43.8
0.5	3.267	7.31							18421	30.2
0.55	3.292	7.36							18566	20.9
0.6	3.310	7.40							18666	14.4
0.65	3.322	7.43							18735	10.0
0.7	3.331	7.45							18782	6.9
0.75	3.336	7.46	2.139	314	1.96	0.081	0.008	6.1	18815	4.8
0.8	3.340	7.47	2.306	314	1.79	0.056	0.006	5.6	18838	3.3
0.85	3.343	7.48	2.474	314	1.67	0.038	0.004	5.2	18854	2.3
0.9	3.345	7.48	2.641	314	1.59	0.027	0.003	4.9	18865	1.6
0.95	3.346	7.49	2.808	315	1.53	0.018	0.002	4.8	18872	1.1
1	3.347	7.49	2.976	315	1.50	0.013	0.001	4.6	18877	0.7
1.05	3.348	7.49	3.143	315	1.47	0.009	0.001	4.6	18881	0.5
1.1	3.348	7.49	3.310	315	1.45	0.006	0.001	4.5	18883	0.4
1.15	3.349	7.49	3.478	315	1.44	0.004	0.000	4.5	18885	0.2

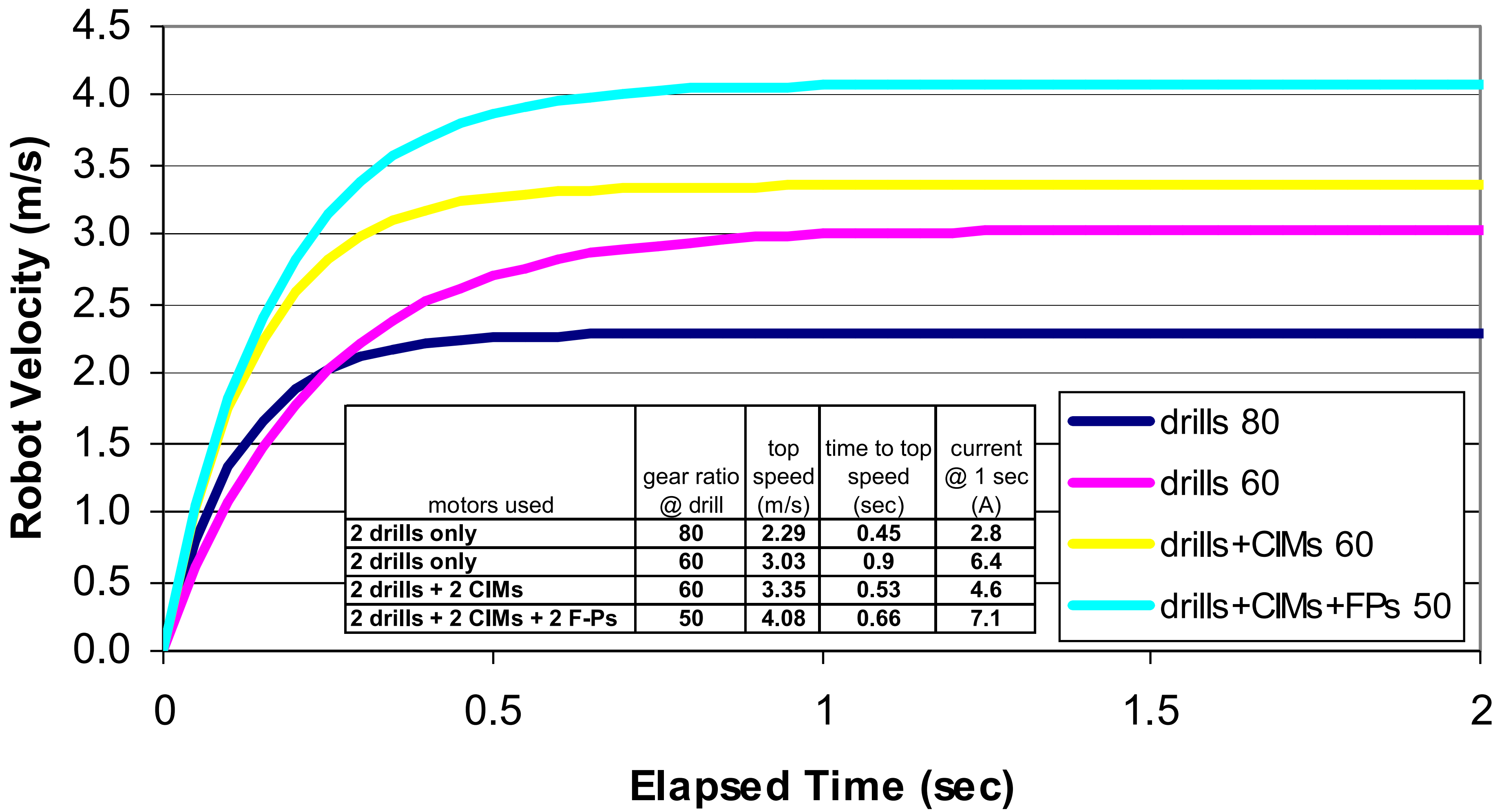
see John V-Neun's presentation and team 229's website

available on the web at www.huskiebrigade.com





Simulation Results



motors used	gear ratio @ drill	top speed (m/s)	time to top speed (sec)	current @ 1 sec (A)
2 drills only	**80**	**2.29**	**0.45**	**2.8**
2 drills only	**60**	**3.03**	**0.9**	**6.4**
2 drills + 2 CIMs	**60**	**3.35**	**0.53**	**4.6**
2 drills + 2 CIMs + 2 F-Ps	**50**	**4.08**	**0.66**	**7.1**

Example results for 130 lb robot

Robot Drive Systems

1. Drive System Requirements
2. Traction Fundamentals
3. FIRST Motors
4. Gearing Fundamentals
5. System Design Condition
6. Practical Considerations

Reliability

Keep it simple!

- makes it easier to design and build
- will get it up and running much sooner
- makes it easier to fix when it breaks

Get it running quickly

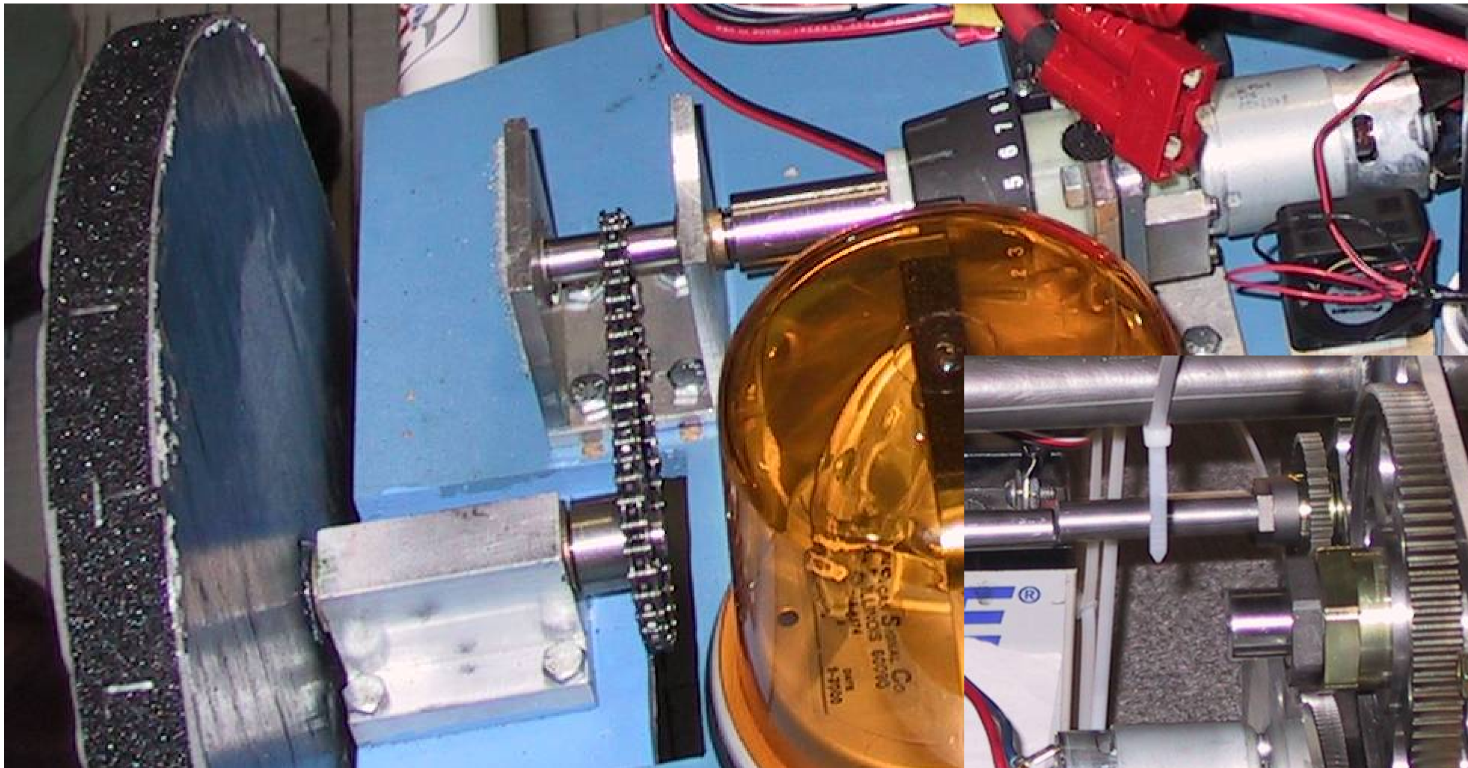
- find out what you did wrong sooner
- allow drivers some practice (the most important thing)
- chance to fine-tune
- chance to get the control system on the robot
- when testing, make sure weight of machine is about right

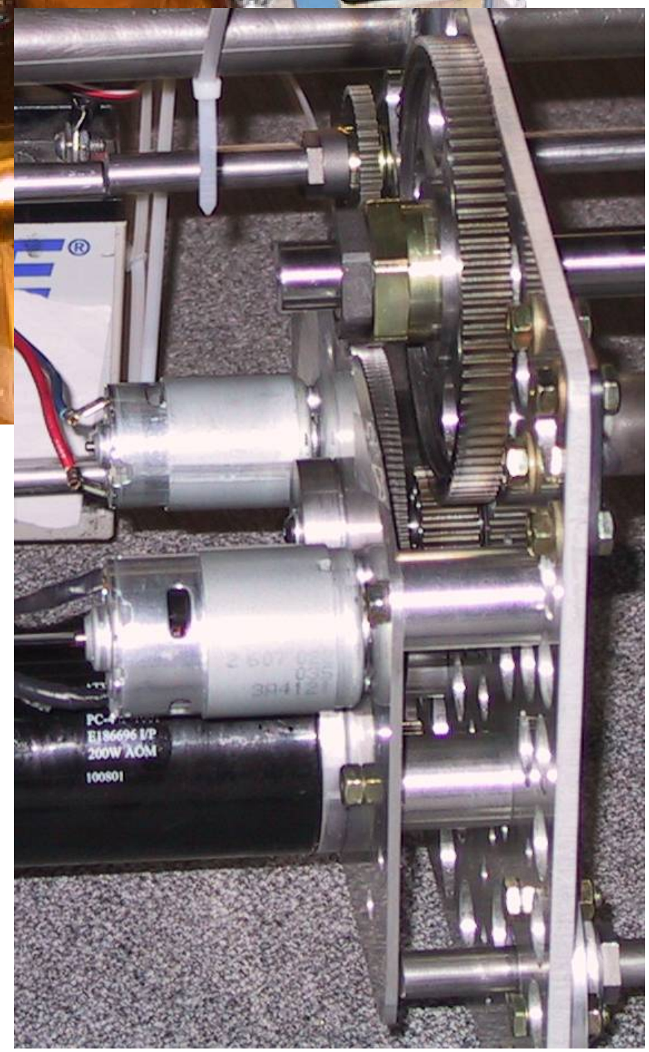
Reliability, cont'd

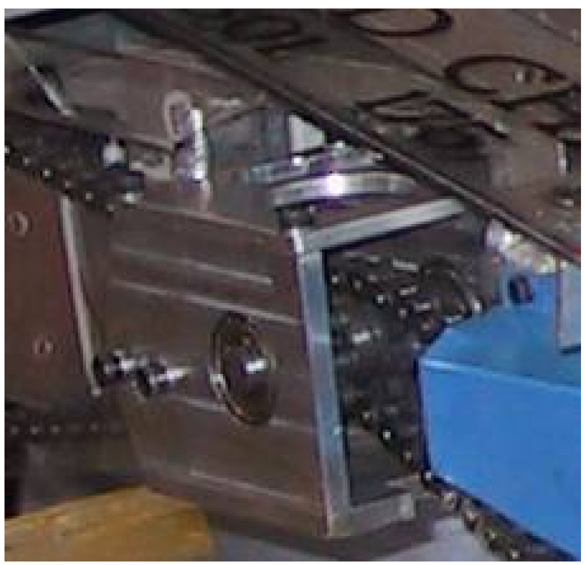
Strongly consider assembly + disassembly
- think about where wrench clearance is needed
- visualize how it will be assembled, repaired
- provide access holes to enable motor swaps

Use reliable fastening systems
- often this is where things break, come loose, etc.
- take special care where shaft alignment is concerned

Support shafts appropriately
- reduced deflections will reduce friction
- reduced friction will improve durability & controllability




E186696 I/P
200W AOM
100801



Best New Drive System Component!

Drive System Fundamantals

QUESTIONS?

Drive System Terms

we already cover these in detail

1. Gear Ratio: Can be described many ways
   - Motor Speed / Output Speed

2. Efficiency - Work lost due to drive losses
   - Friction, heat, misalignment

3. Friction Force - Tractive (pushing) force generated between floor and wheel.

4. W is rotational speed & V is linear Speed (velocity)

5. N1 is # of teeth on input gear/sprocket

6. N2 is # of teeth on output gear/sprocket