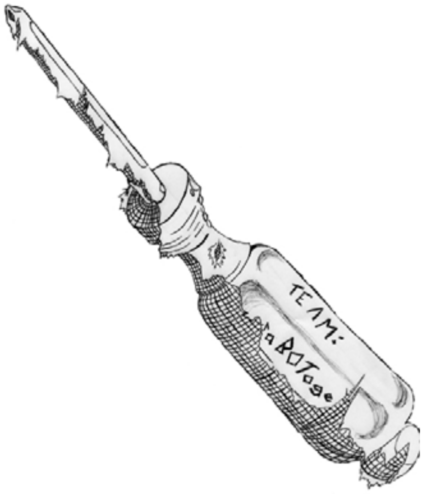
Drive-train Basics



Team 1640

Clem McKown - mentor

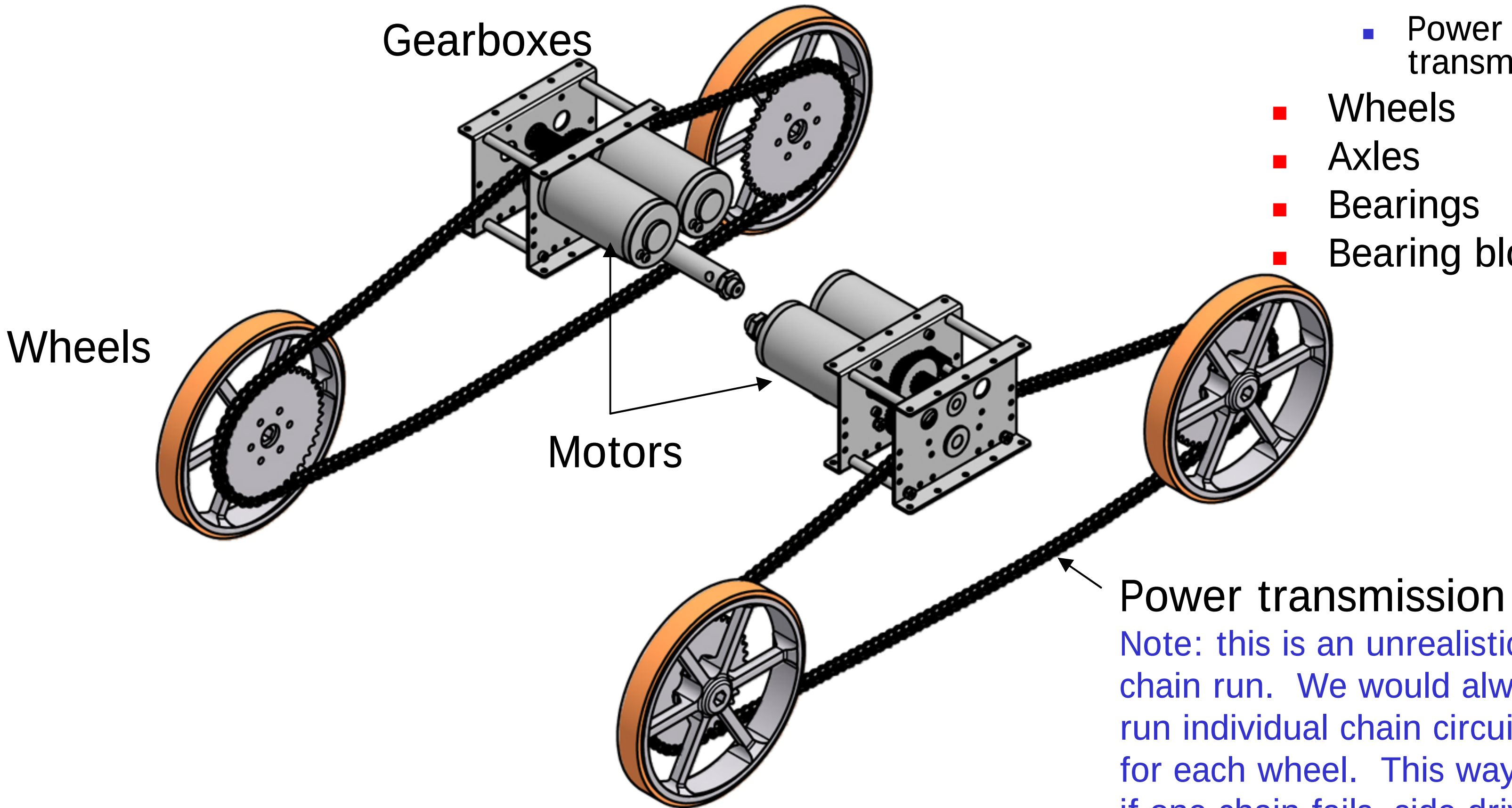
October 2009 (r3)

Topics

- What's a Drive-train?
- Basics
  - Components
  - Propulsion
  - Drivetrain Model
- Center of Mass Considerations
- Automobile versus robot tank drive
- 4wd versus 6wd robot tank drive
- Some Conclusions & Good Practices
- Unconventional Drive-trains
- Introducing Concept Pivot Chassis

What's a Drive-train?

- *The mechanism that makes the robot move*
- Comprising:
  - Motors
  - Transmissions
    - Gearboxes
    - Power transmission
  - Wheels
  - Axles
  - Bearings
  - Bearing blocks



Note: this is an unrealistic chain run. We would always run individual chain circuits for each wheel. This way, if one chain fails, side drive is preserved.

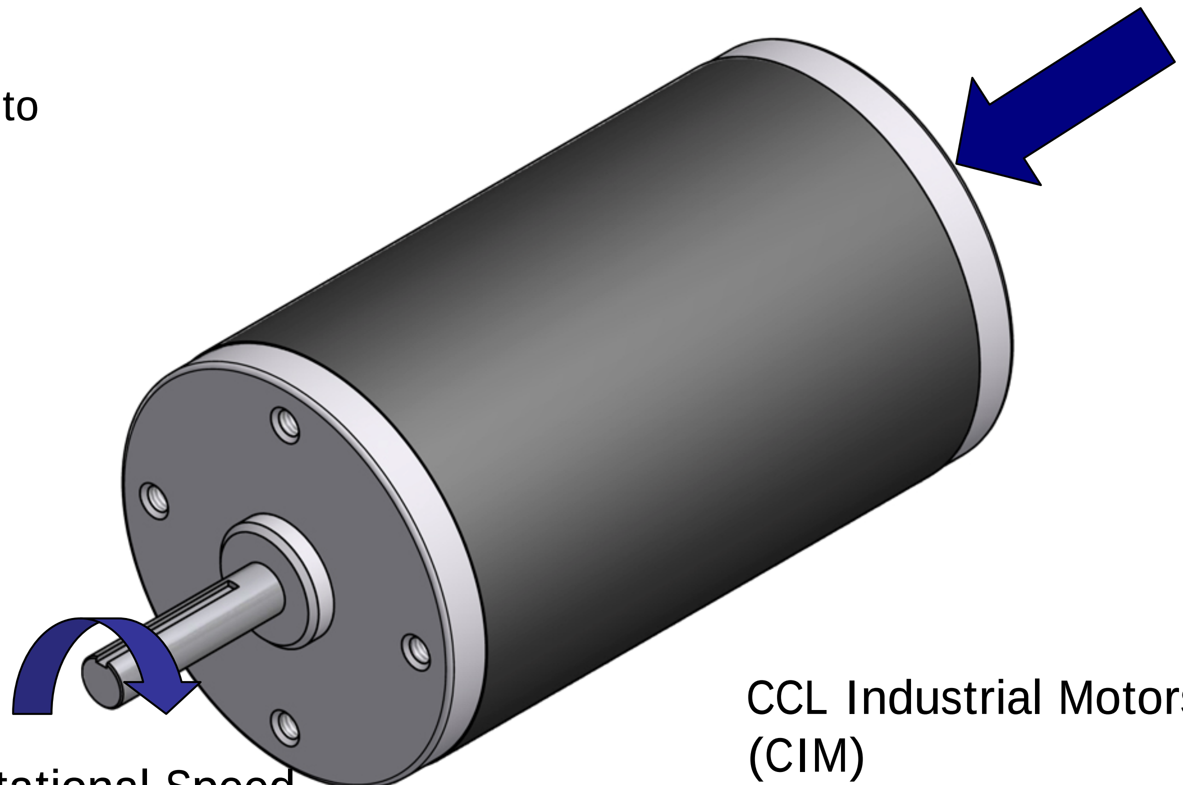
Basics - Components

- Motors
- Transmission
  - Gear Reduction (optional shifting)
  - Power transmission to wheels
- Wheels
- Axles
- Bearings
- Bearing blocks

Basics - Motors

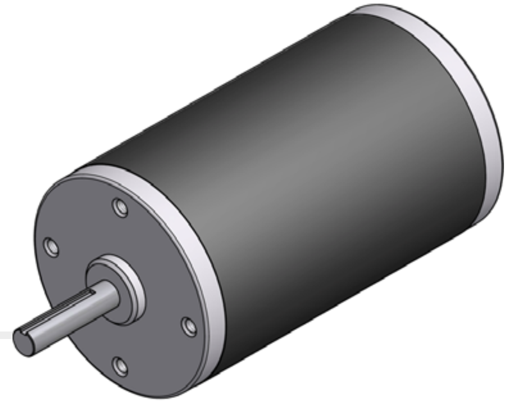
- Electrical Power (W)
  - 12 V DC
  - Current per Motor performance
  - Controlled via Pulse Width Modulation (PWM)

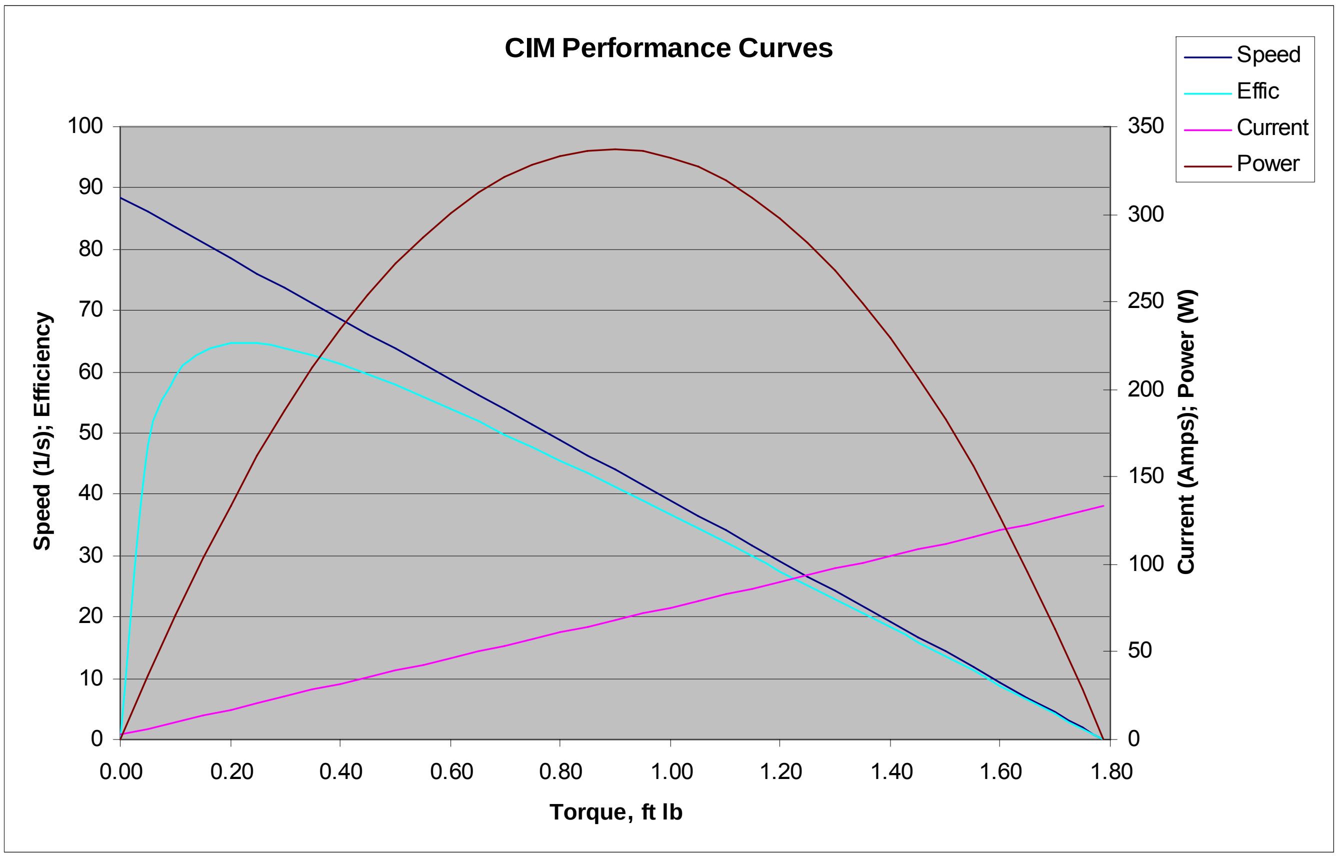
- Motors convert electrical power (W) to rotational power (W)
- Power output is controlled via Pulse Width Modulation of the input 12 V DC



CCL Industrial Motors (CIM)
FR801-001

Basics - Motors



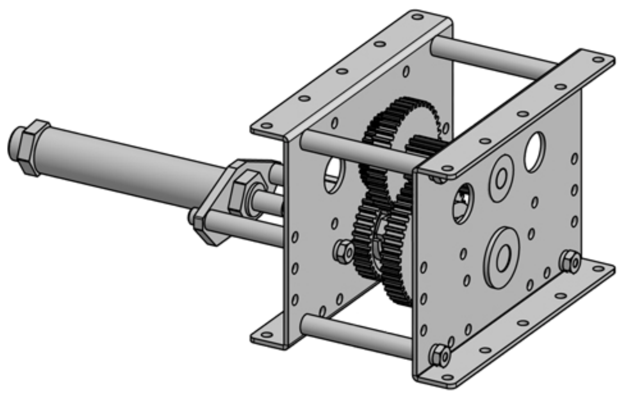


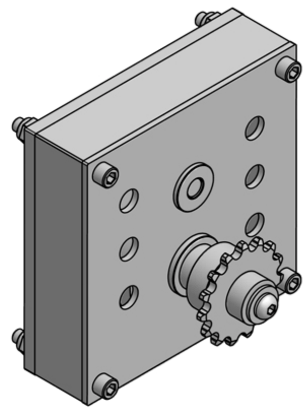
- Motor curve @ 12 V DC
- Allowed a max of (4) CIM Motors on the Robot
- Motors provide power at too low torque and too high speed to be directly useful for driving robot wheels
- Each CIM weighs 2.88 lb

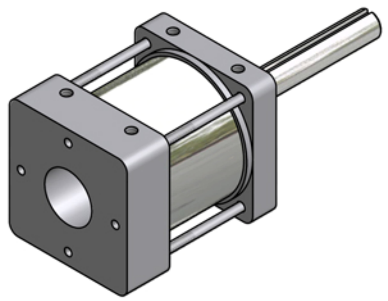
Basics – Transmission

- Transmission
  - Reduces motor rotational speed and increases torque to useful levels to drive wheels
  - Transmits the power to the wheels
  - Optional – it may allow shifting gears to provide more than one effective operating range
    - High gear for speed
    - Low gear for fine control
- Generally consists of two parts
  - Gearbox for gear reduction & shifting
  - Power transmission to the wheels – which may include additional gear reduction as well

Gearbox examples







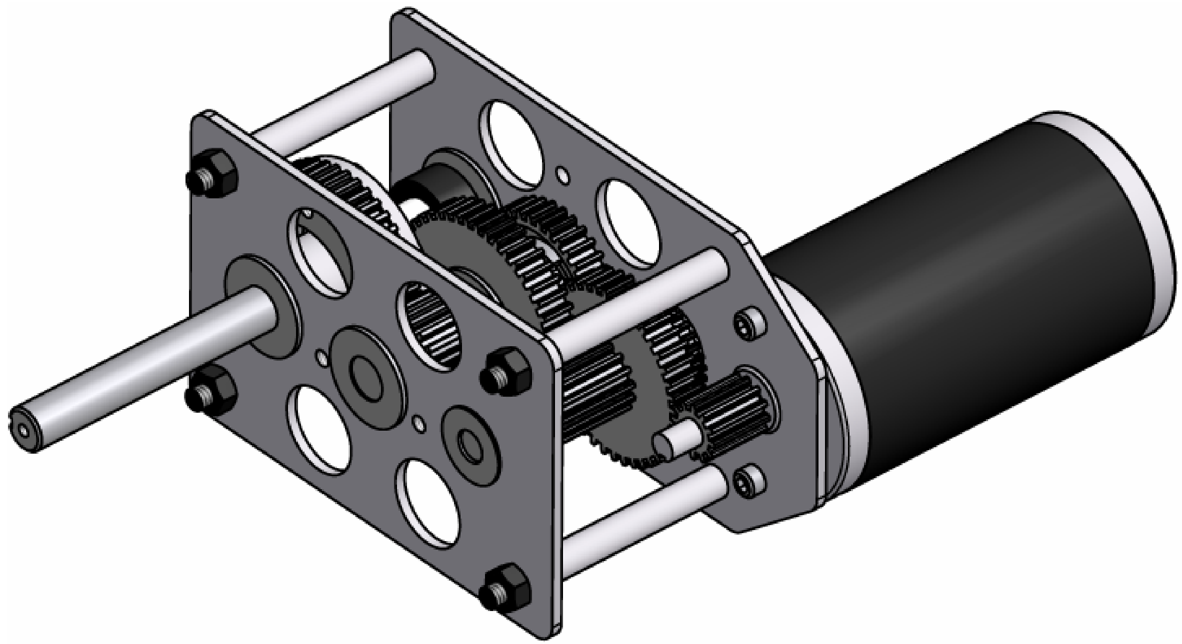
- AndyMark 2-Speed
- 10.67:1 and 4.17:1
- Output: 12 tooth sprocket
- 1 or 2 CIM motors
- 4.14 lb
- Used on our previous 2 robots

- AndyMark Toughbox
- 5.95:1 or 8.45:1
- Output: ½" keyed shaft
- 1 or 2 CIM motors
- 2.5 lb

- Bainbots planetary gearbox
- 9:1; 12:1 or 16:1 (2-stage)
- Output – ½" keyed shaft
- 1 CIM motor (2 available)
- 2.56 lb
- Can drive wheel directly
- 3:1 or 4:1 reduction/stage
- 1 to 4 stages available
- 3:1 to 256:1 available

1640 Custom gearbox

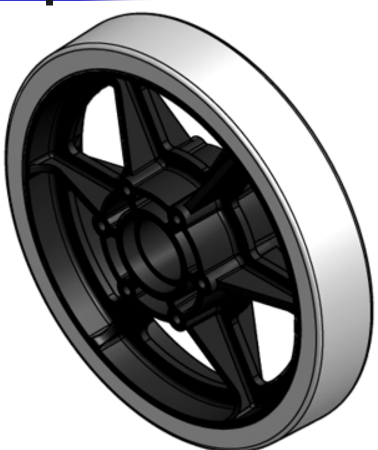
- Modified AndyMark 2-Speed
- Sprocket output replaced w/ 20-tooth gear & additional 45:20 (9:4) reduction added
- Direct-Drive
- ½” shaft output
- 9.4:1 & 24:1
- 1 or 2 CIM motors
- Used successfully on Dewbot V



Power Transmission

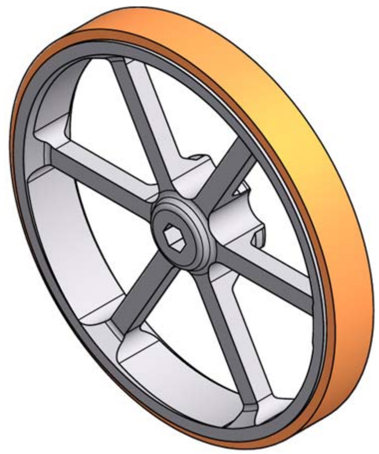
- Chains & Sprockets
  - Traditional
  - Allows further reduction (via sprocket sizing)
  - 3/8” pitch chain
    - Steel – 0.21 lb/ft
    - Polymer – 0.13 lb/ft
- Direct (w/ Bainbots gearbox)
- Gears (Team 25)
- Shafts
- Use your imagination

Basics – Wheels - examples



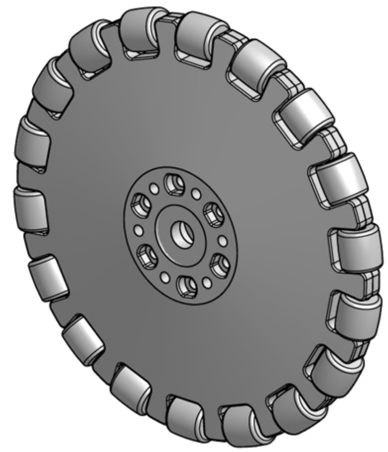
Kit Wheel
6" diameter

m = 0.48 lb

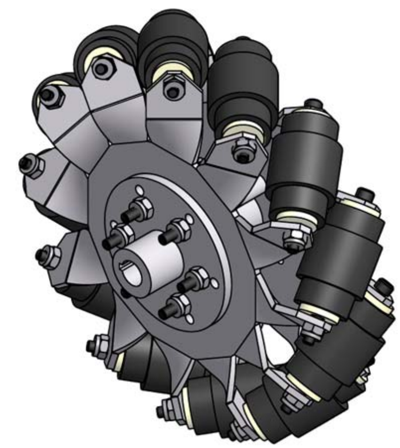


Performance Wheel
8" diameter
High-traction tread

m = 1.41 lb



Omni Wheel
8" diameter
Circumferential rollers
$\mu_{t,s}$ = 1.07
$\mu_{t,k}$ = 0.90
$\mu_{x,s}$ = 0.20
$\mu_{x,k}$ = 0.16
m = 1.13 lb



Mecanum Wheel
8" diameter
Angled rollers
$\mu_{t,s}$ = 0.70
$\mu_{t,k}$ = 0.60
$\mu_{x,s}$ = 0.70
$\mu_{x,k}$ = 0.60
m = 2.50 lb
There are left & right mecanums

Drive Basics - Propulsion

F_f = Friction Force
$F_f = \mu F_n$

μ = coefficient of friction

For objects not sliding relative to each other

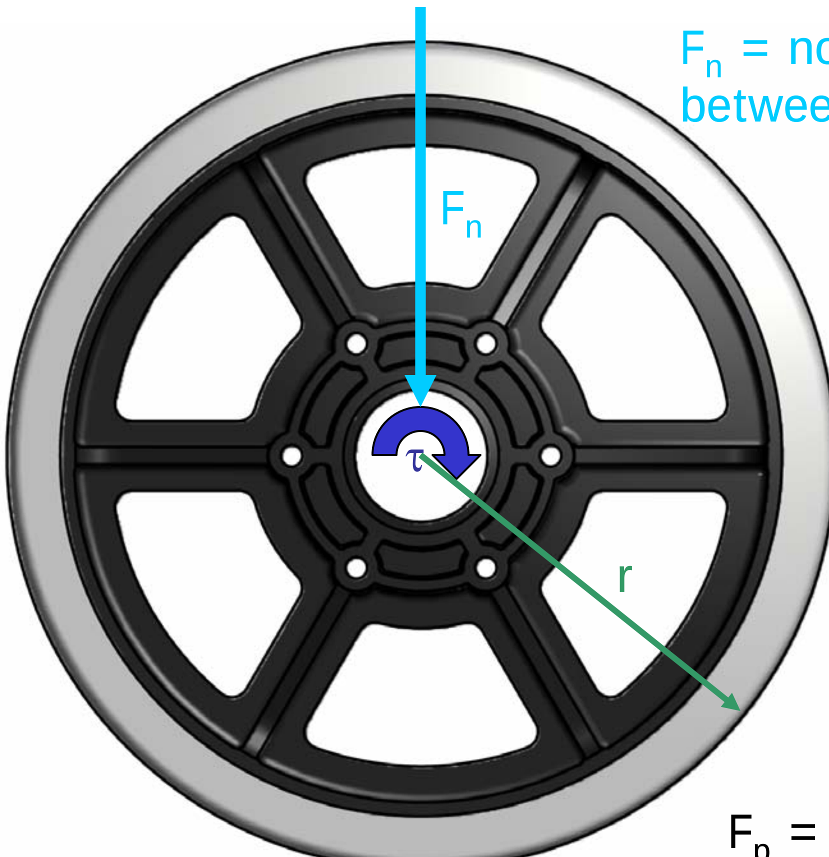
$\mu = \mu_s$ (static coefficient of friction)

For objects sliding relative to each other

$\mu = \mu_k$ (kinetic coefficient of friction)

as a rule, $\mu_s > \mu_k$
(this is why anti-lock brakes are such a good idea)

F_n = normal force between frictive surfaces



For a 120 lb_m robot with weight equally distributed over four wheels, F_n would be 30 lb_f at each wheel.

The same robot with six wheels would have F_n of 20 lb_f at each wheel (at equal loading).

τ = torque
r = wheel radius

F_d = Drive Force
$F_d = \tau / r$

μ_s
μ_k

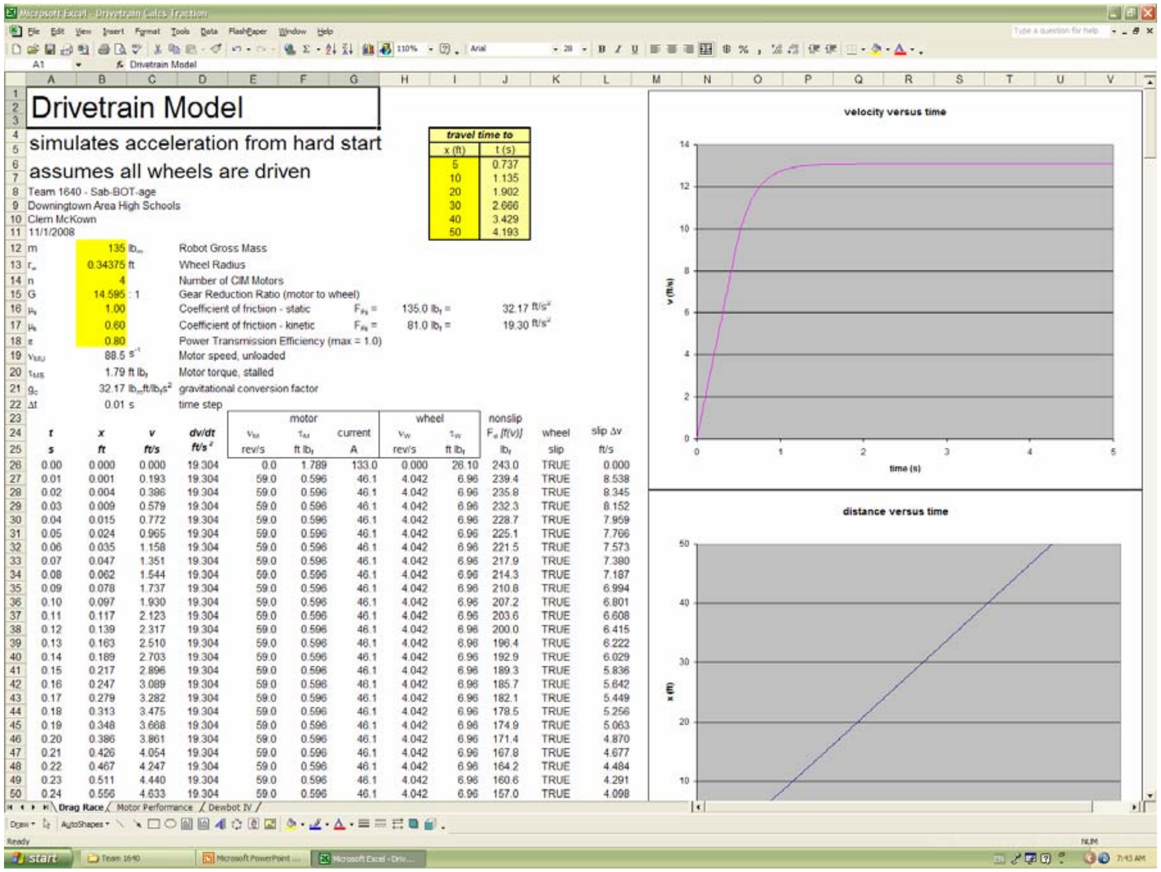
F_p = Propulsive Force

For wheels not sliding on drive surface:
$F_p = -F_d$; $F_p \leq F_{f/s}$
For wheels slipping on drive surface: $F_p = F_{f/k}$

$$\frac{dv}{dt} = \frac{G n \tau_{MS} g_c}{m r_W} \left(1 - \frac{\tau_{ML}}{\tau_{MS}} - \frac{G}{2\pi r_W v_{MU}} v \right)$$

Drive-train Model

- Excel-based model calculates acceleration, velocity & position versus time for a full-power start
- Predicts and accounts for wheel slippage
- Allows “what if?” scenarios
- A tool for drive-train design

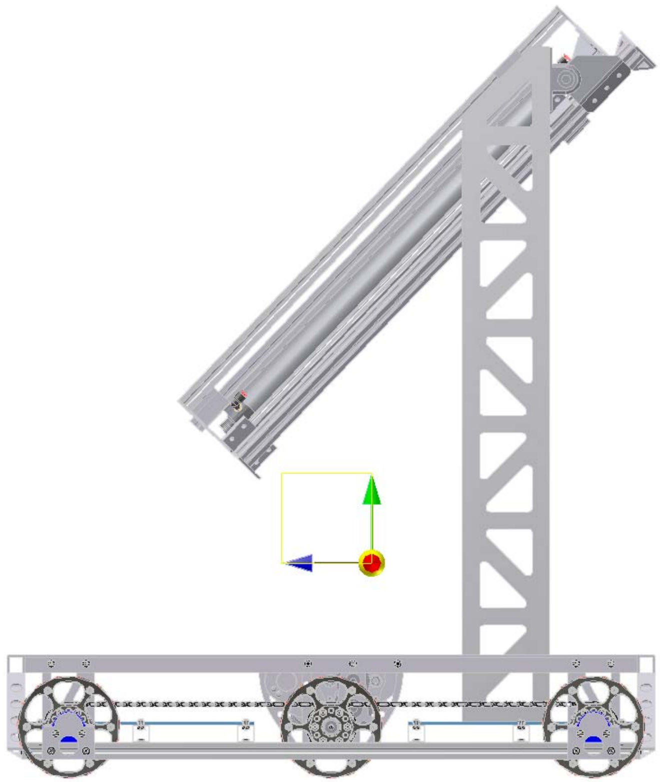


Center of Mass considerations

Help! I've fallen and I can't score anymore

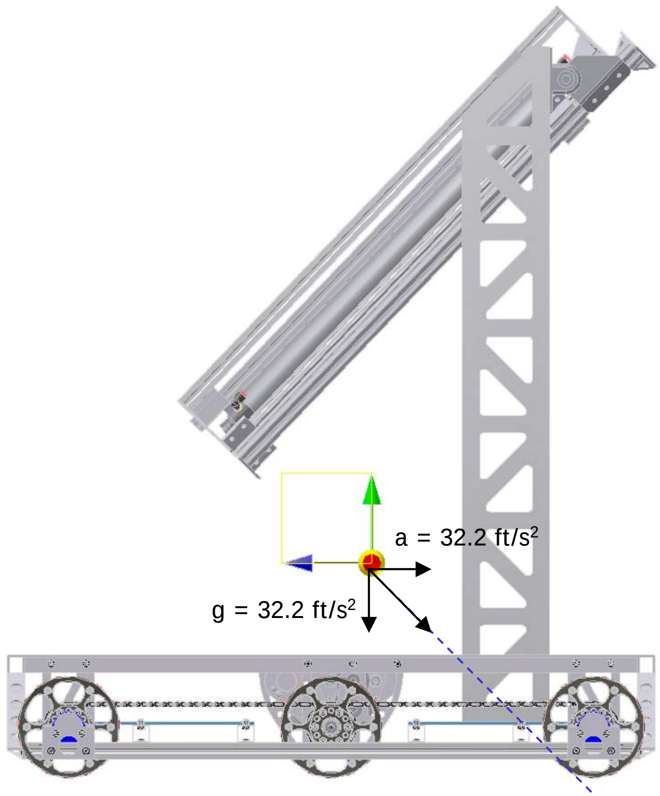
Center of Mass

- The point in space about which an object (robot) balances
- If the *projection* of the CoM falls outside the wheelbase, the robot will tip over

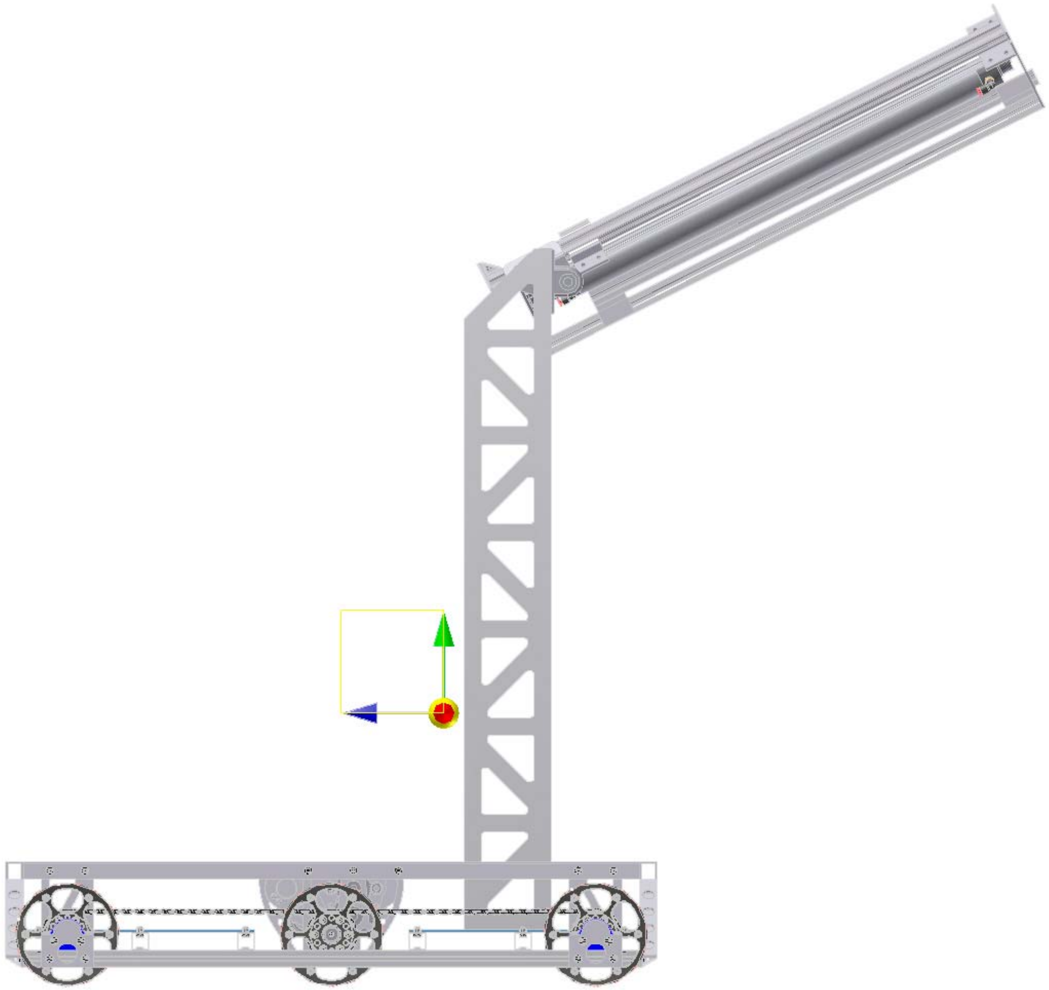


Center of Mass Projection

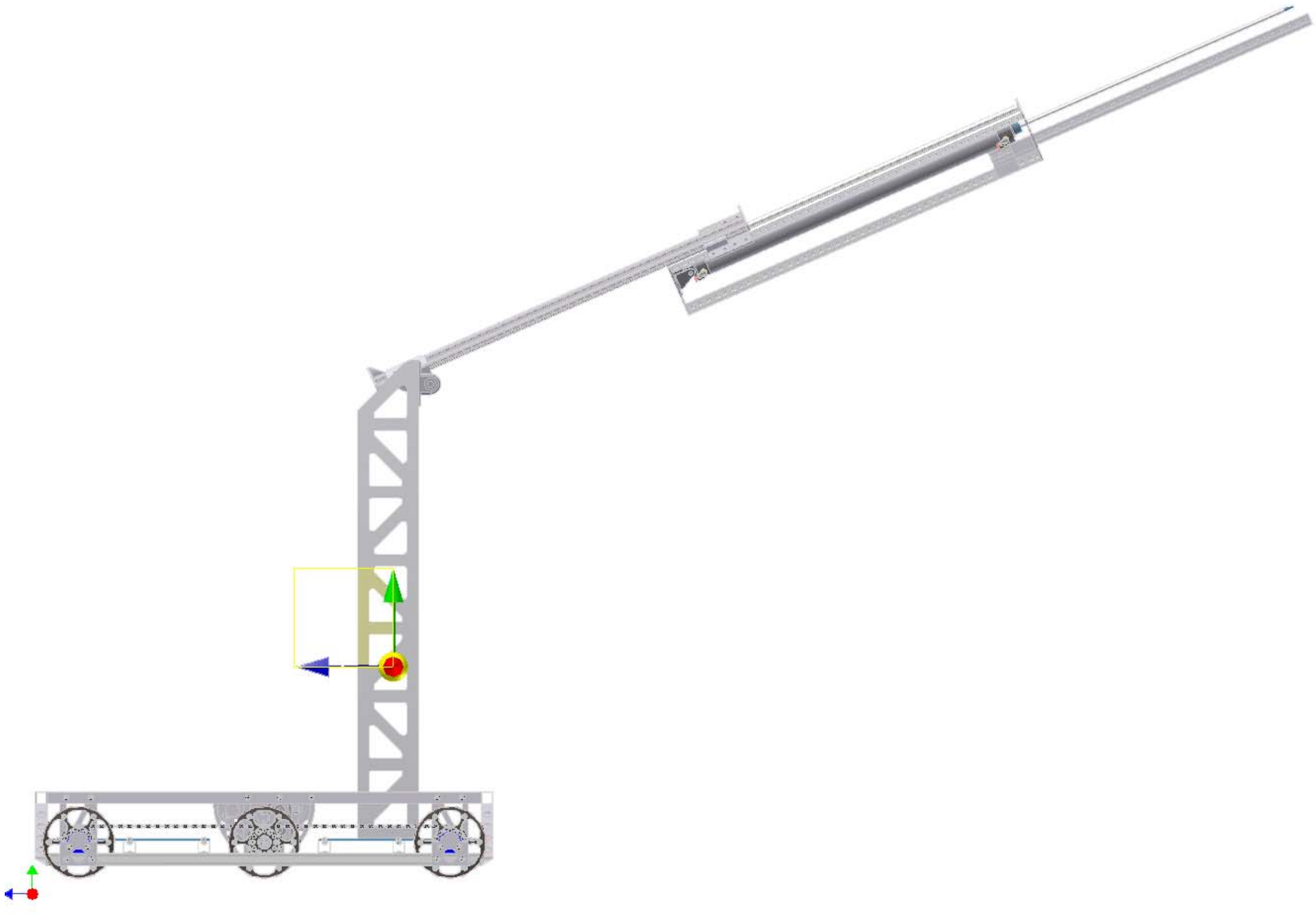
- Straight down if robot is not accelerating
- Straight down on a ramp also (but the projected point shifts)
- Projection shifted by inverse of acceleration vector (see diagram at right)
- Remember that stopping and turning are also accelerations



The CoM can move as the robot deploys...



...it can move a lot!

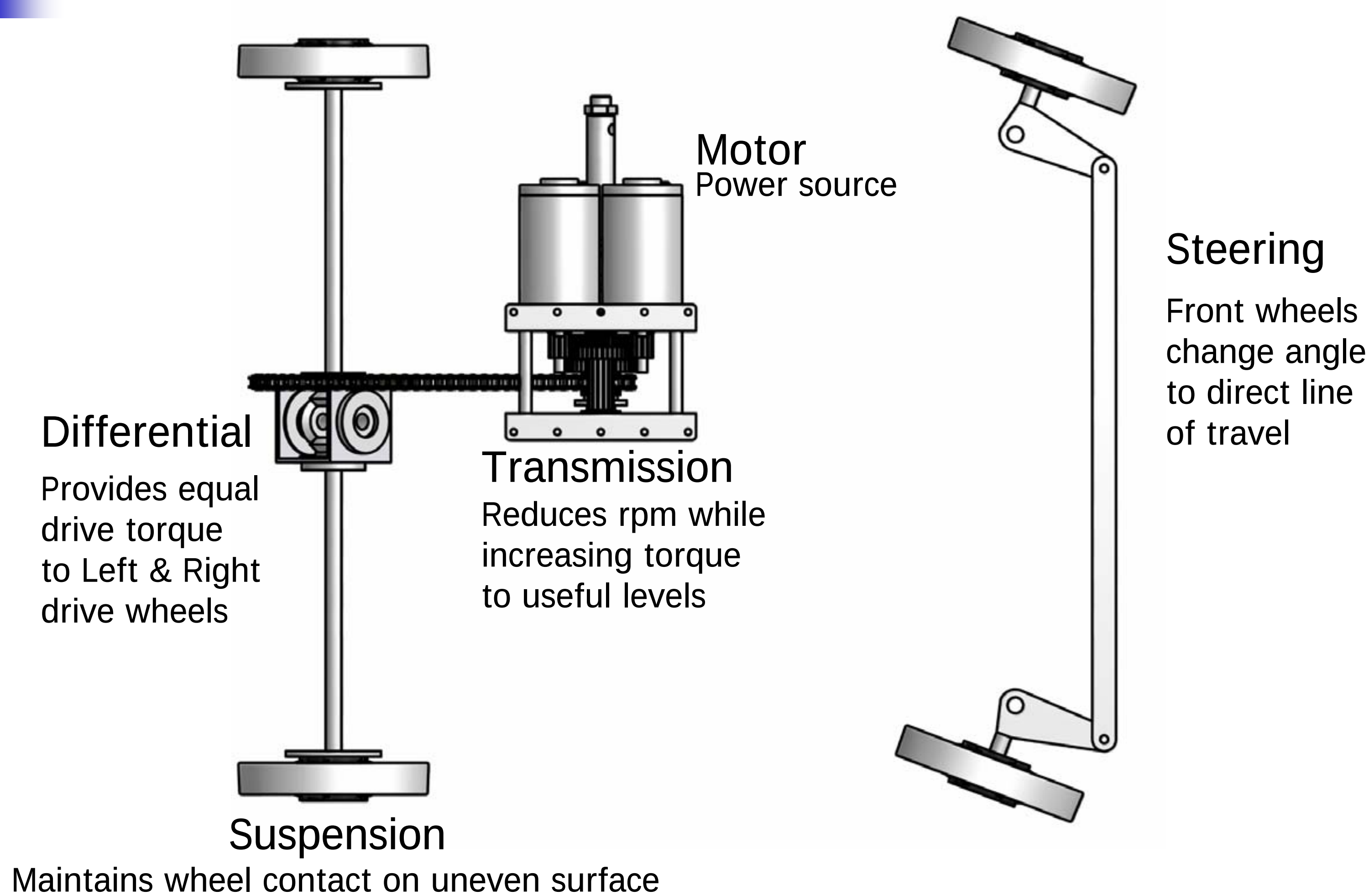


How Robots Drive

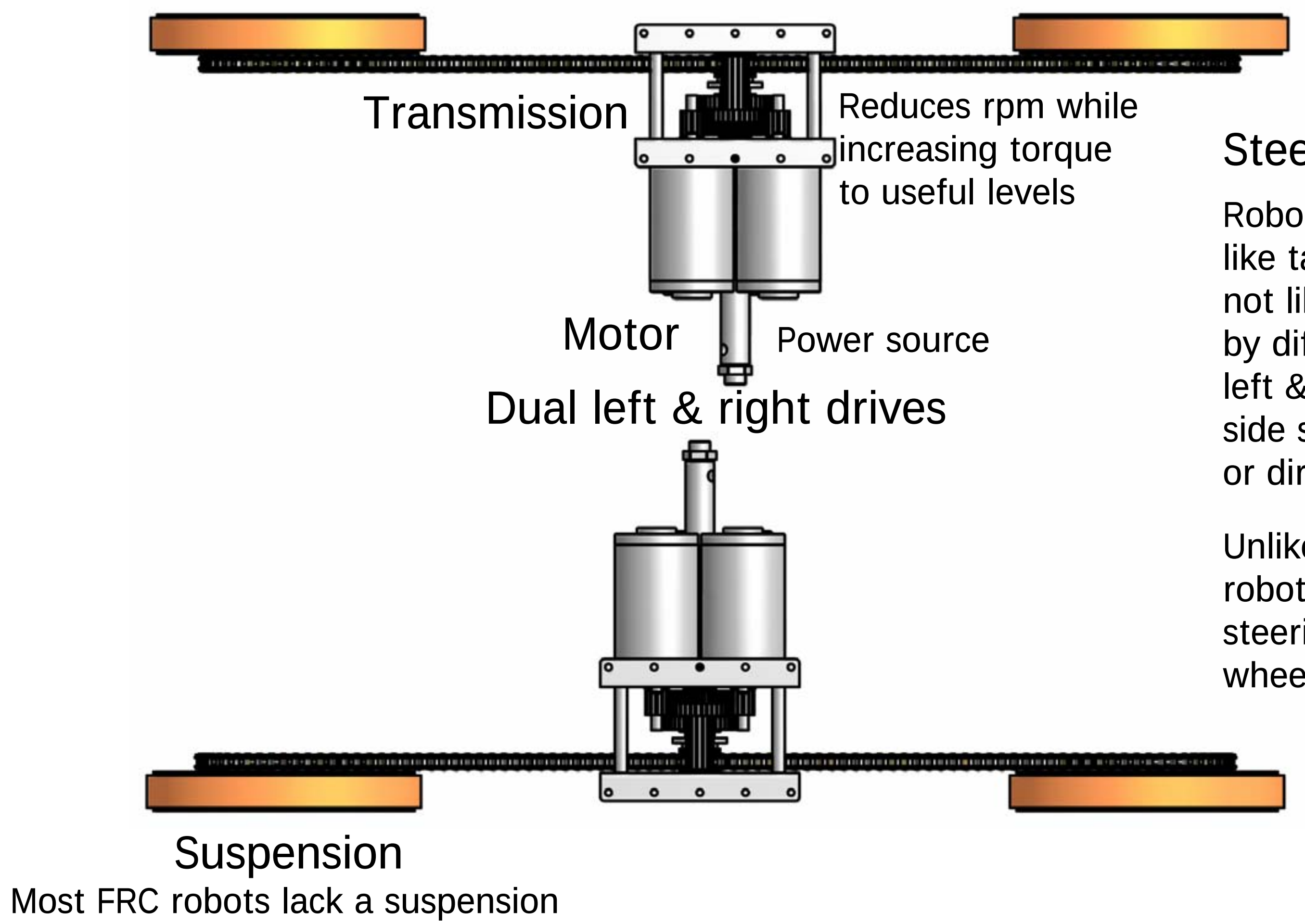
Automobile driving

Robot (Tank) driving

How an automobile drives



How a (typical) robot drives



Steering

Robots steer like tanks - not like cars - by differential left & right side speeds or directions

Unlike a car, robot (tank) steering requires wheel sliding

Car - Robot Comparison

Automobile Drive	*Robot (Tank) Drive*
+ Efficient steering	- High energy steering
+ Smooth steering	- Steering hysterisis
+ Avoids wheel sliding	- Wheels slide to turn
+ Low wheel wear	- High wheel wear
- Large turn radius	+ Zero turning radius
- Cannot turn in place	+ Turns in place
- Limited traction	+ Improved traction

4wd – 6wd Comparison

Propulsion Force (F_p) – Symmetric 4wd

Propulsion Force per wheel

Rolling without slipping:

$F_{p/w} = \tau/r_w$ - up to a maximum of $F_{p/w} = \mu_s F_n$

Pushing with slipping: $F_{p/w} = \mu_k F_n$

Assumptions / Variables:

- τ = torque available at each axle
- m = mass of robot
- F_n = Normal force per wheel
  - = ¼ m g/g_c (SI F_n = ¼ m g)
  - – evenly weighted wheels
- r_w = wheel radius

Robot Propulsion Force

$$F_{p/R} = \Sigma F_{p/w}$$

Rolling without slipping: $F_{p/R} = 4\tau/r_w$

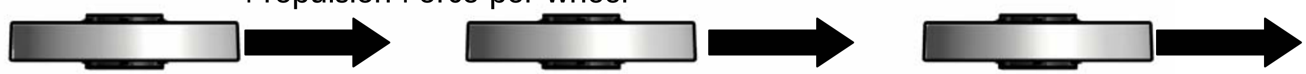
Pushing with slipping: $F_{p/R} = 4\mu_k F_n$

Does not depend on evenly weighted wheels → $F_{p/R} = \mu_k m g/g_c$

(SI): $F_{p/R} = \mu_k m g$

F_p – Symmetric 6wd

Propulsion Force per wheel



Rolling without slipping:

$F_{p/w} = {}^{2}/_{3}\tau/r_w$ - up to a maximum of $F_{p/w} = \mu_s F_n$

Pushing with slipping: $F_{p/w} = \mu_k F_n$

Assumptions / Variables:

- ${}^{2}/_{3}\tau$ = torque available at each axle
  - same gearing as 4wd w/ more axles
- m = mass of robot
- F_n = Normal force per wheel
  - $= {}^{1}/_{6}\, m\, g/g_c$ (SI $F_n = {}^{1}/_{6}\, m\, g$)
  - – evenly weighted wheels
- r_w = wheel radius

Robot Propulsion Force

$$F_{p/R} = \Sigma F_{p/w}$$

Rolling without slipping: $F_{p/R} = 6\ {}^{2}/_{3}\tau/r_w = 4\tau/r_w$

Pushing with slipping: $F_{p/R} = 6\mu_k F_n$

$F_{p/R} = \mu_k\, m\, g/g_c$

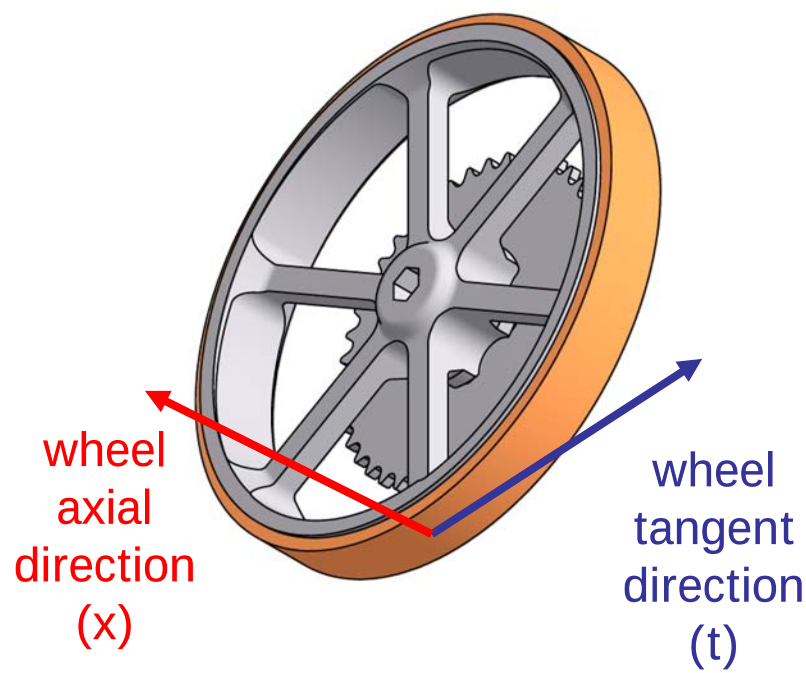
(SI): $F_{p/R} = \mu_k\, m\, g$

Conclusion

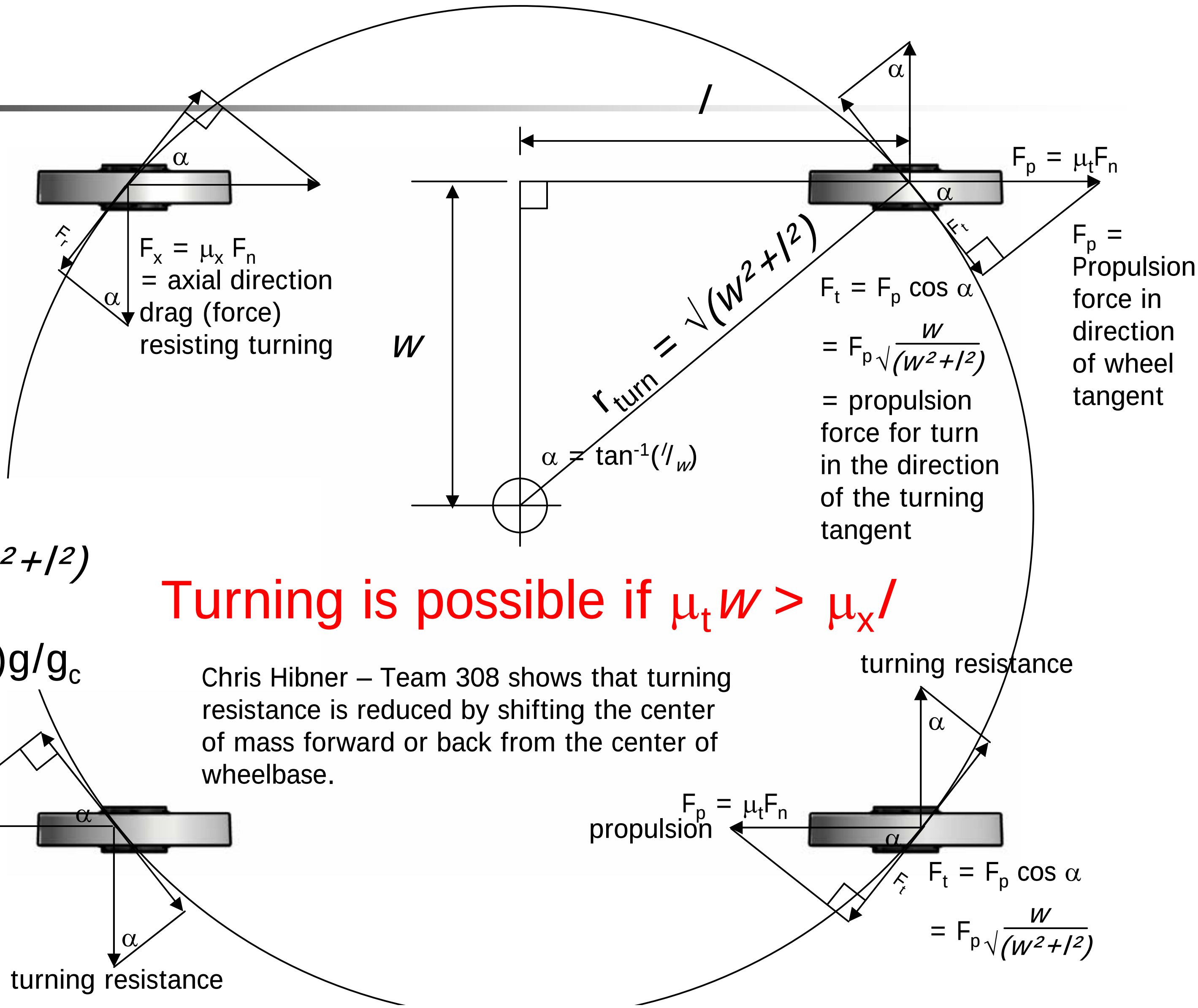
Would not expect 6wd to provide any benefit in propulsion (or pushing) vis-à-vis 4wd (all other factors being equal)

Stationary turning of symmetric robot

- Assume center of mass and turn axis is center of wheelbase
- Some new terms need an introduction:
  - μ_t – wheel/floor coefficient of friction in wheel tangent direction
  - μ_x – wheel/floor coefficient of friction in wheel axial direction (omni-wheels provide $\mu_x << \mu_t$)
  - F_x – wheel drag force in wheel axis direction



Stationary turning – 4wd



$F_r = F_x \sin\alpha$

$= F_x \frac{l}{\sqrt{(w^2+l^2)}}$

= drag force against turn in the direction of the turning tangent

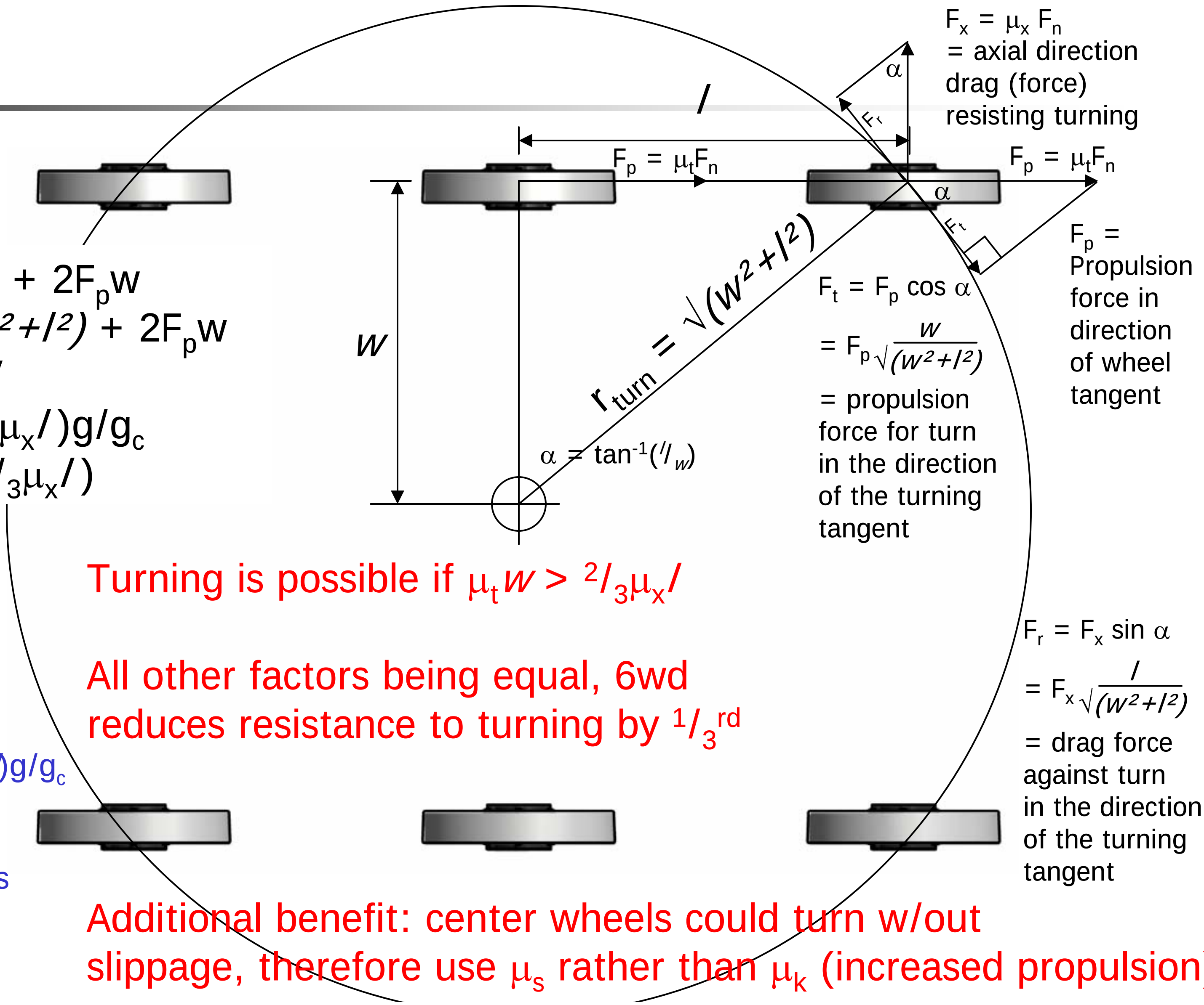
$$\tau_{turn} = 4(F_t - F_r)r_{turn}$$
$$= 4(F_t - F_r)\sqrt{(w^2+l^2)}$$
$$= 4(F_p w - F_x l)$$
$$= m(\mu_t w - \mu_x l)g/g_c$$

Turning is possible if $\mu_t w > \mu_x l$

Chris Hibner – Team 308 shows that turning resistance is reduced by shifting the center of mass forward or back from the center of wheelbase.

Stationary turning – 6wd

$$\tau_{turn} = 4(F_t - F_r)r_{turn} + 2F_p w$$
$$= 4(F_t - F_r)\sqrt{(w^2 + l^2)} + 2F_p w$$
$$= 6F_p w - 4F_x l$$
$$= m(\mu_t w - {}^2/_3 \mu_x l)g/g_c$$
$$\text{(SI)} = mg(\mu_t w - {}^2/_3 \mu_x l)$$



But this is based on Equal weight distribution
Analysis indicates center wheels support disproportionate weight: 40-60% of total - @ 40%:

$$\tau_{turn} = m(\mu_t w - (1-.4)^2/_3 \mu_x l)g/g_c$$
$$= m(\mu_t w - 0.4\mu_x l)g/g_c$$

$\therefore$ turning benefit of 6wd is considerable

Turning is possible if $\mu_t w > {}^2/_3 \mu_x l$

All other factors being equal, 6wd reduces resistance to turning by $^1/_3$rd

Additional benefit: center wheels could turn w/out slippage, therefore use μ_s rather than μ_k (increased propulsion)

4wd – 6wd Tank Drive Comparison

4wd Tank Drive	*6wd Tank Drive*
+ Simplicity	- More complex
+ Weight	- Weight (2 wheels)
	- Constrains design
o Traction	o Traction
o Stability	o Stability
- Turning	+ Turning
- Steering hysterisis	+ Less hysterisis
- Wheel wear	+ Reduced wear
	+ Ramp climbing

Conclusions & Good Practices

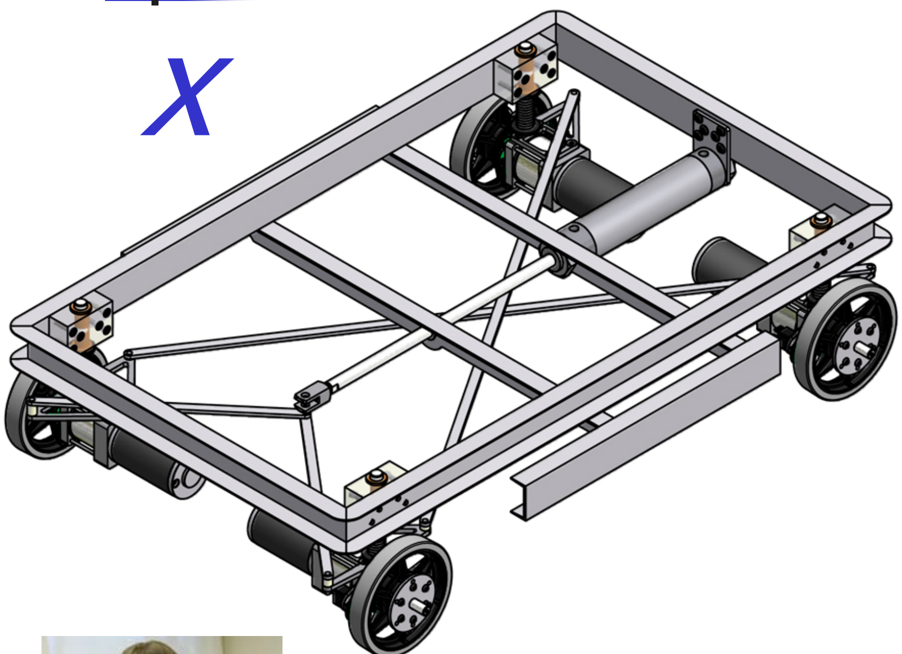
- Provided that all wheels are driven, all other factors being equal, the number of drive wheels does not influence propulsion or pushing force available.
- The existence of undriven wheels, which support weight but do not contribute to propulsion, necessarily reduce the available pushing force - these should be avoided.
- Omni wheels can improve tank steering – but increase vulnerability to sideways pushing.
- For a robot with a rectangular envelope, given wheelbase, mass and center of gravity, (4) wheels (driven or not) provide the maximum stability. Additional wheels neither help nor hurt.
- A common side drive-train (linked via chains or gears) has a propulsion advantage over a drive-train having individual motors for each wheel: As wheel loading (F_n) changes and becomes non-uniform, a common drive-train makes more torque available to the loaded wheels. Power is available were you've got traction.
- For traction: Maximize weight & friction coefficients
- For tank turning: Provide adequate torque to overcome static (axial) friction coefficient

Unconventional Drive-trains

Food for thought

Bi-Axial Drive ("Twitch") a unique drive from Team 1565

x



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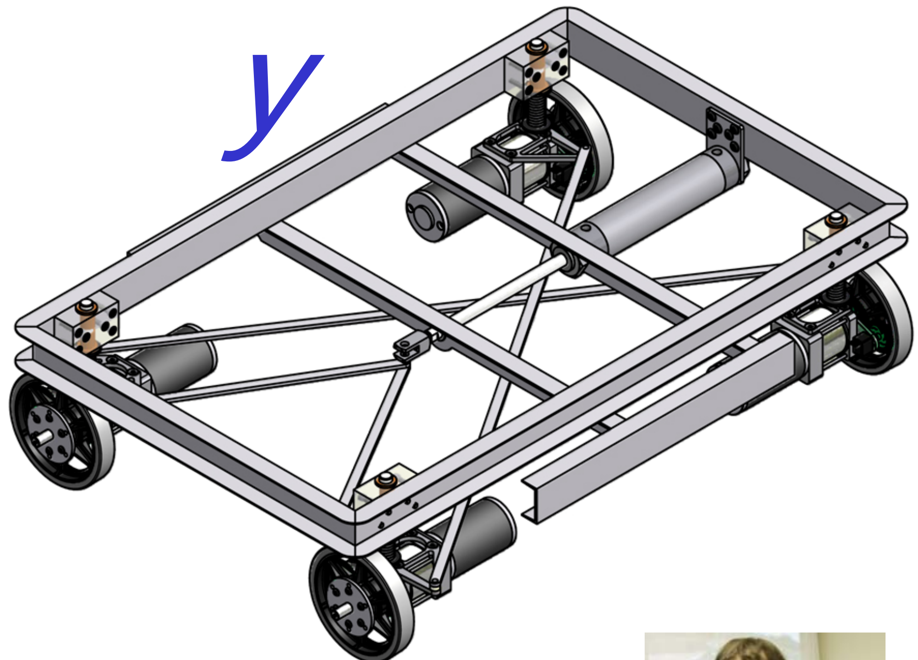
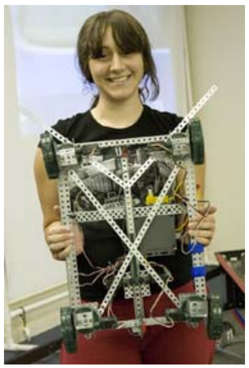
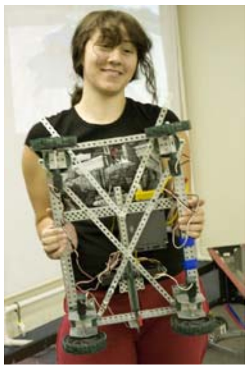


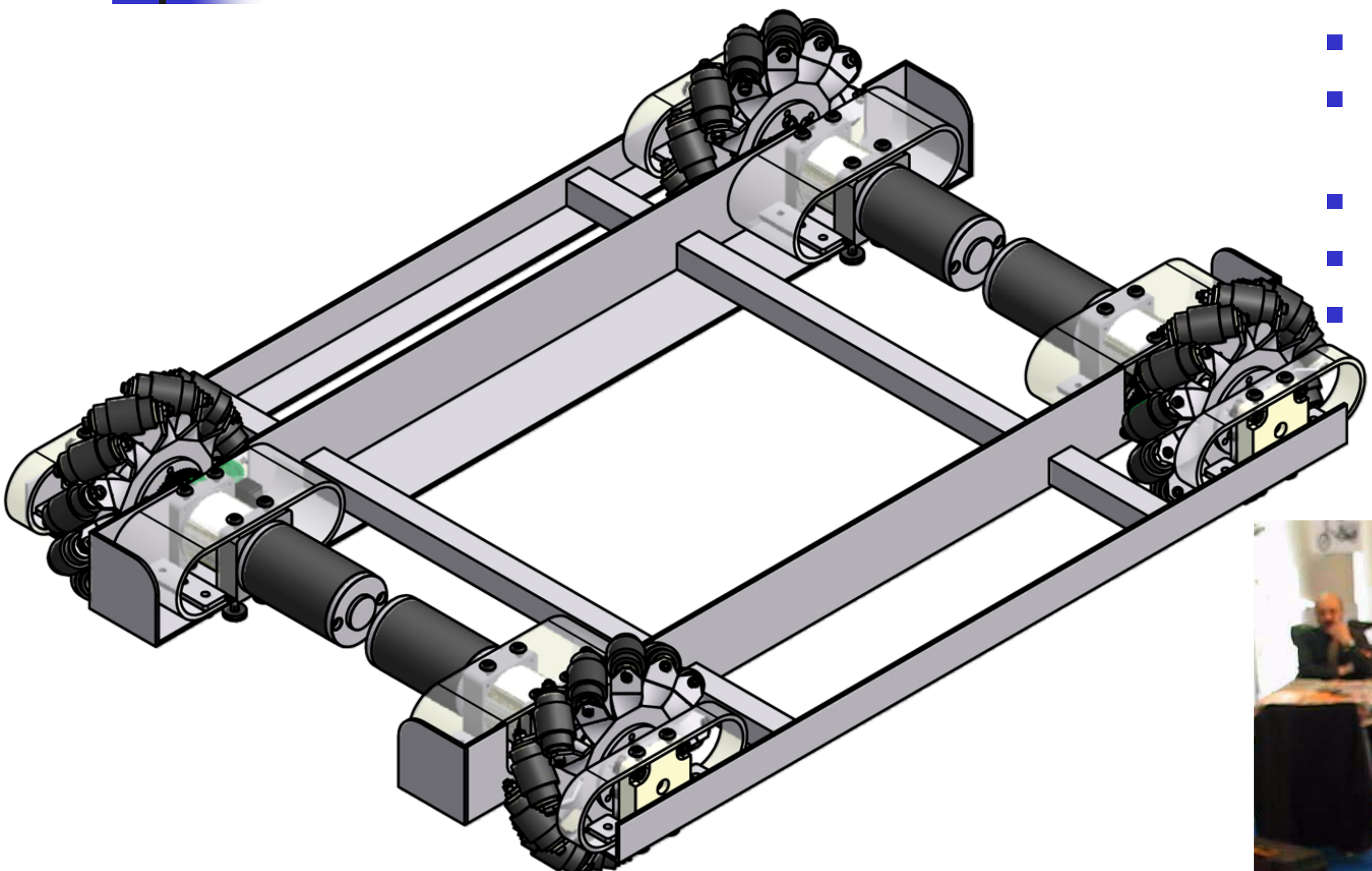


- 2-axis drive (not 2d)
- Fast (pneumatic) switch
- Agile
- Steers well in y-mode
- Poor steering x-mode

- Any of (4) sides can be front (always drive forward)
- Compatible w/ suspension
- 1 speed

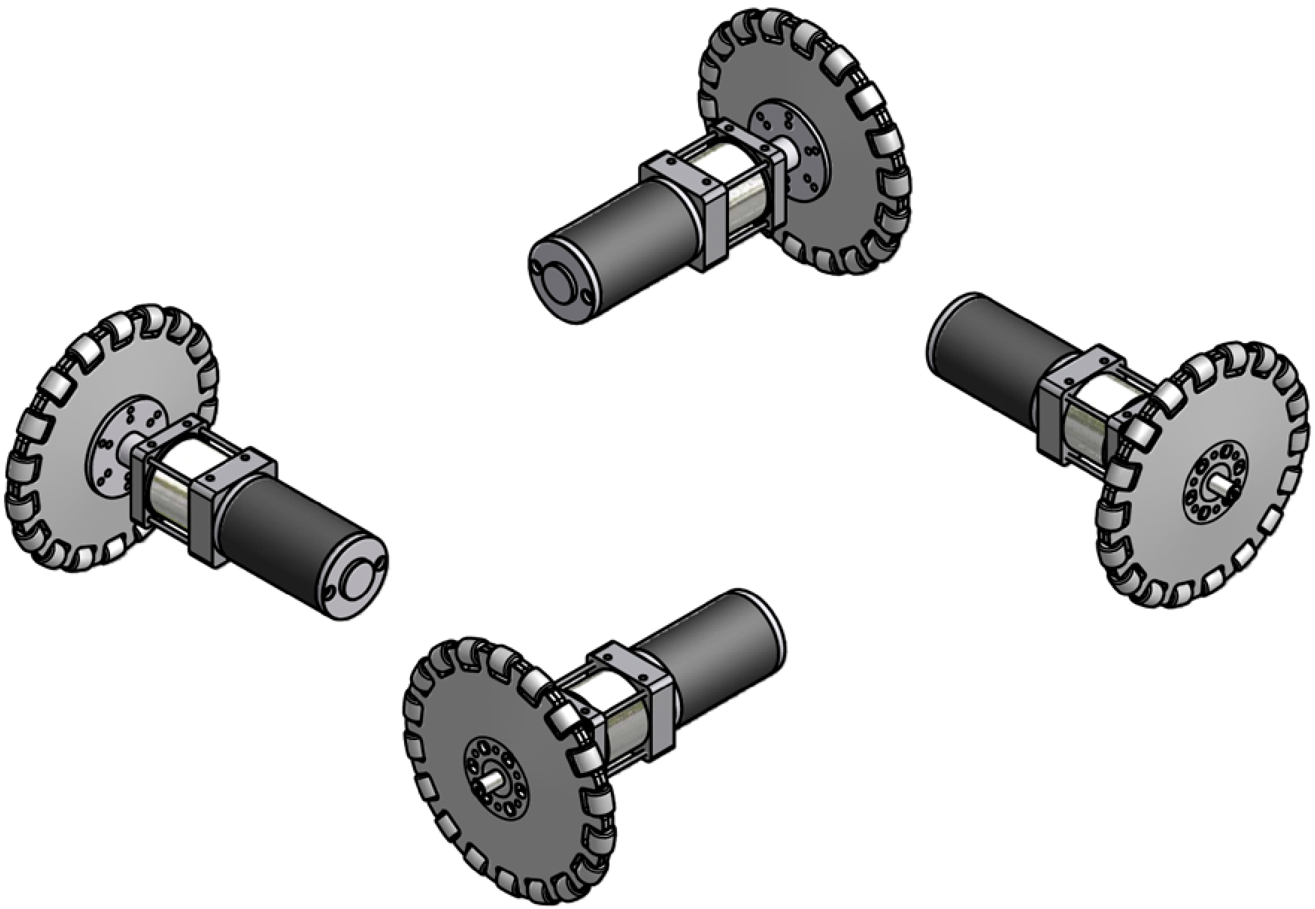


Mecanum Drive
true 2-d maneuverability



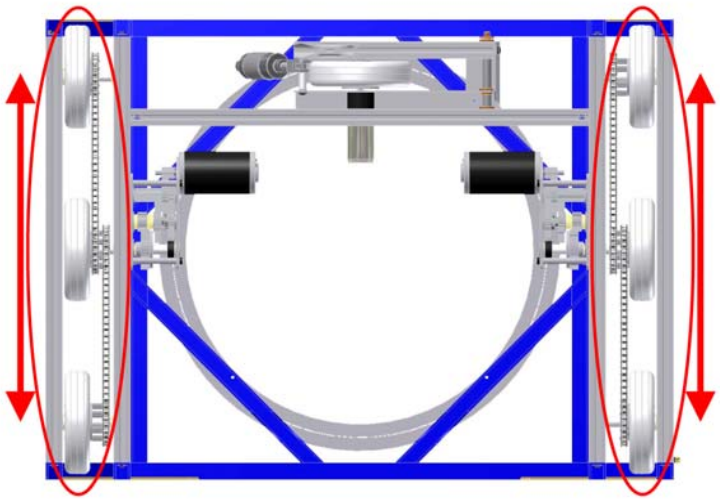
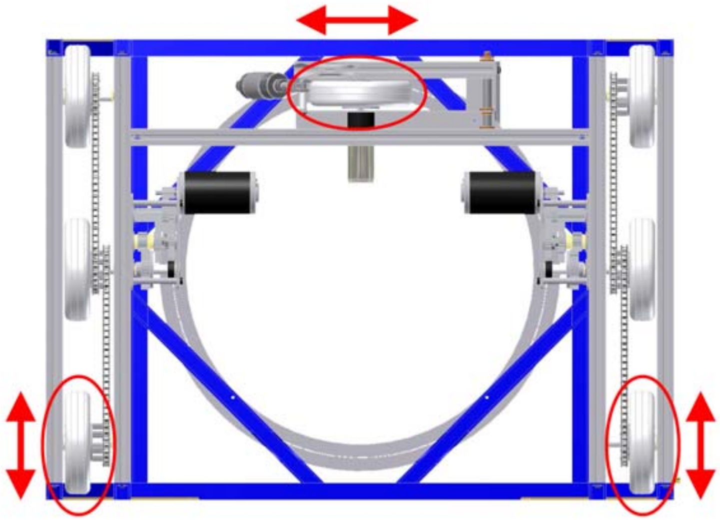
- 2-d drive
- Compatable w/ suspension
- Very cool
- Moderately popular
- 1640 has no experience

"Daisy Drive" (Square Bot) 2-d maneuverability w/ limits



- Drive used by Miss Daisy (Team 341)
- Favorite of Foster Schucker (Vex)
- 2-d drive
- agile
- Can't climb ramps
- Not a pusher
- Smaller "platform" therefore poorer stability

6 + 1 = 3

- Dewbot V utilized a novel dual-mode drive-train for Lunacy
  - 6wd wide orientation
  - 7th Wheel back-center to provide fast pivoting ability

Drive Attribute Summary

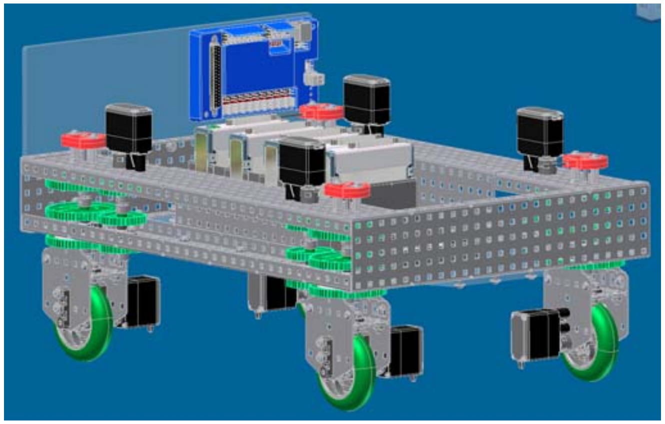
	Steering Ease	Turn Radius	Agility	Traction	Ramp Climbing	
Automobile	++	-	-	-	+	
4wd Tank	-	+	-	++	+	
6wd Tank	+	+	0	++	++	
Twitch	-	+	+	++	+	
Mecanum	+	+	++	+	+	} Speculative
Daisy	+	+	++	-	-	

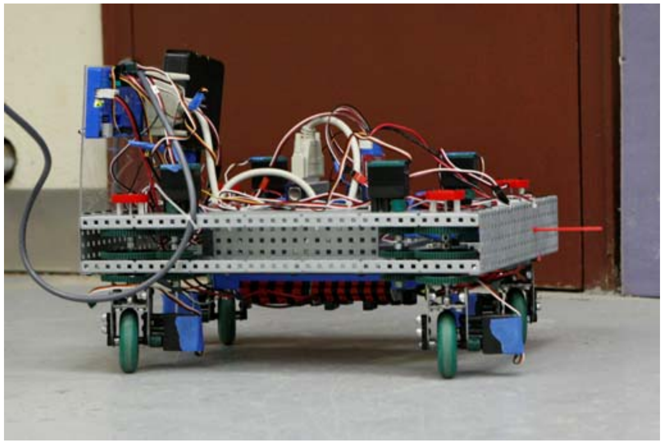
Concept Pivot Chassis

Multi-Mode 4-wheel Pivot Drive design for exceptional maneuverability

Pivot Drive

- 4 wheel drive-train in which each wheel can be steered
- There are two main strategies for Pivot Drive
  - Crab Drive
  - Snake Drive
- Last summer, the team explored multi-mode Pivot Drive





Crab Drive

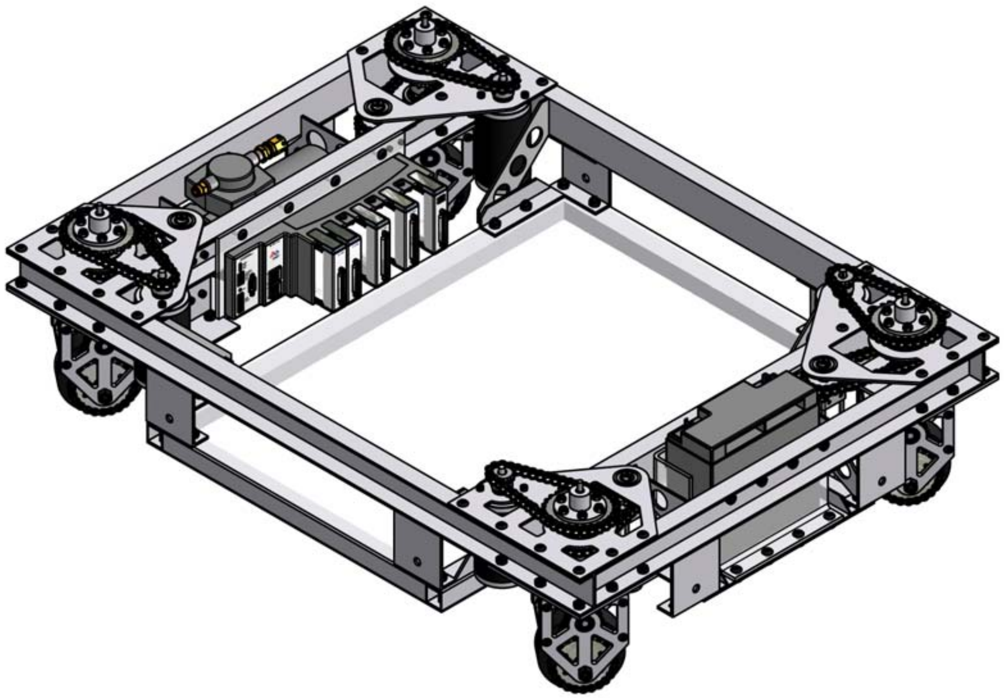
- Pivot Drive in which all 4 wheels pivot together and are aligned together and are all driven at the same speed.
- Provides true 2-d maneuverability
- Requires concentric drive
- Requires infinite pivot
- Straightforward control
- Cannot control chassis orientation
- Team 118's excellent 2007 robot (right) has common drive and steering for all wheels

Snake Drive

- 4-wheel steering
  - Front wheels turn opposite rear wheels
  - Inside wheels turn more than outside
  - Inside wheels drive slower than outside
- Does not have 2-d maneuverability
- Can control chassis orientation
- Can turn around center-point
- Can work bi-axially
- Does not require coaxial drive
- Does not require infinite pivot
- Control is non-trivial

Concept Chassis Design

- Multi-mode Pivot Drive
  - Crab
  - Snake
  - Automobile
  - Tank
- Biaxial
- 4-wheel independent
  - Drive
  - Steering
- Coaxial drive
- Infinite Pivot
- Monitors pivot angle using absolute encoders
- Requires (8) motors to do this



Chassis in Crab Mode

Concept Chassis Design