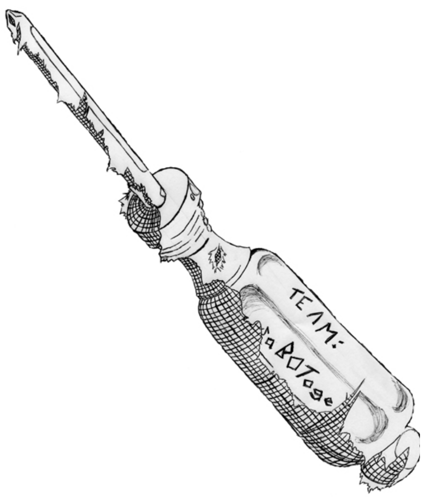
Drivetrain Basics



Team 1640

Clem McKown - mentor

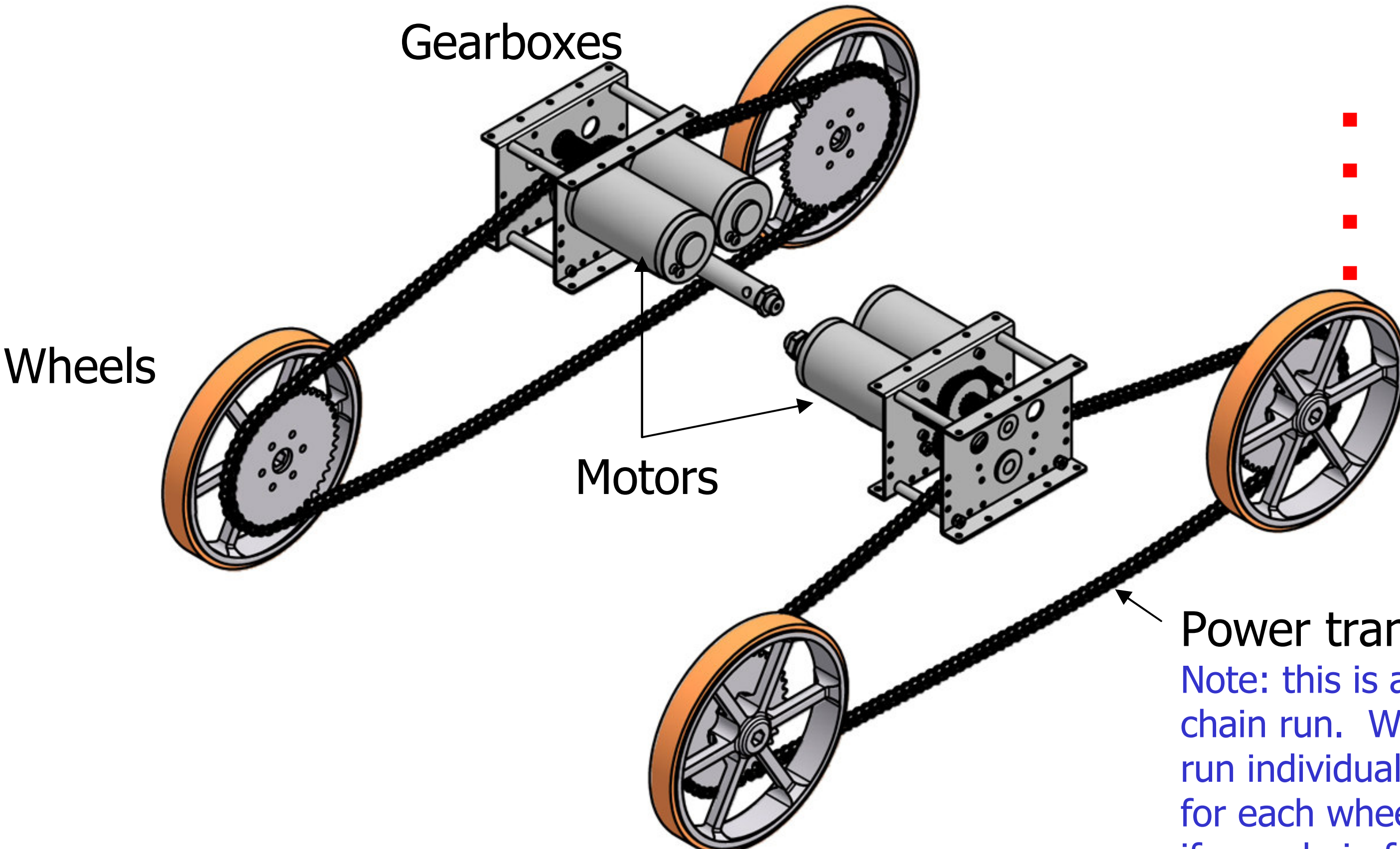
June 2009

Topics

- What's a Drivetrain?
- Basics
  - Components
    - Motor Curves
    - Transmissions
    - Wheels
  - Propulsion
  - Drivetrain Model
- Automobile versus robot (tank) drive
- 4wd versus 6wd robot (tank) drive
- Some Conclusions & Good Practices
- Unconventional Drivetrains
  - "Twitch"
  - Mecanum
  - "Daisy" drive
  - 6 + 1 = 3
- Comparisons

What's a Drivetrain?

- *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.

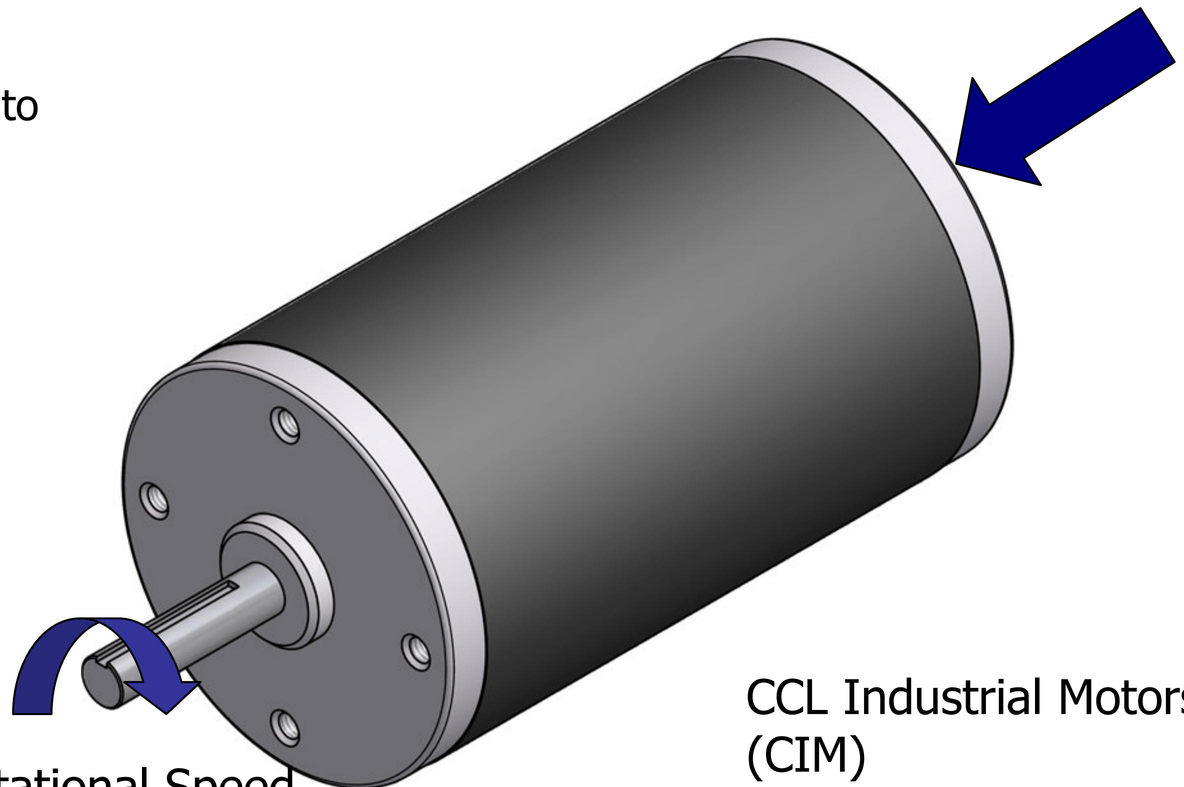
Basics - Components

- Motors
- Transmission
  - Reduction Gearbox (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)

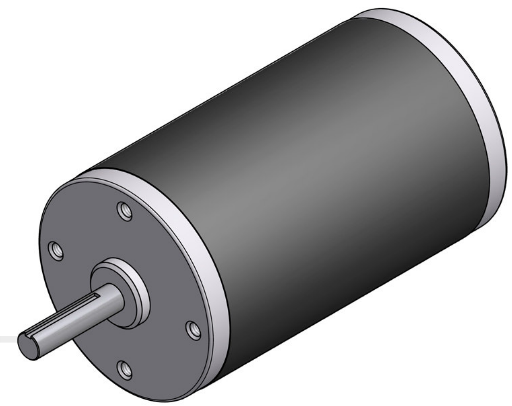
- Motors convert electrical power (W) to rotational power (W)
- Power output is controlled via Pulse Width Modulation of the input 12 V DC

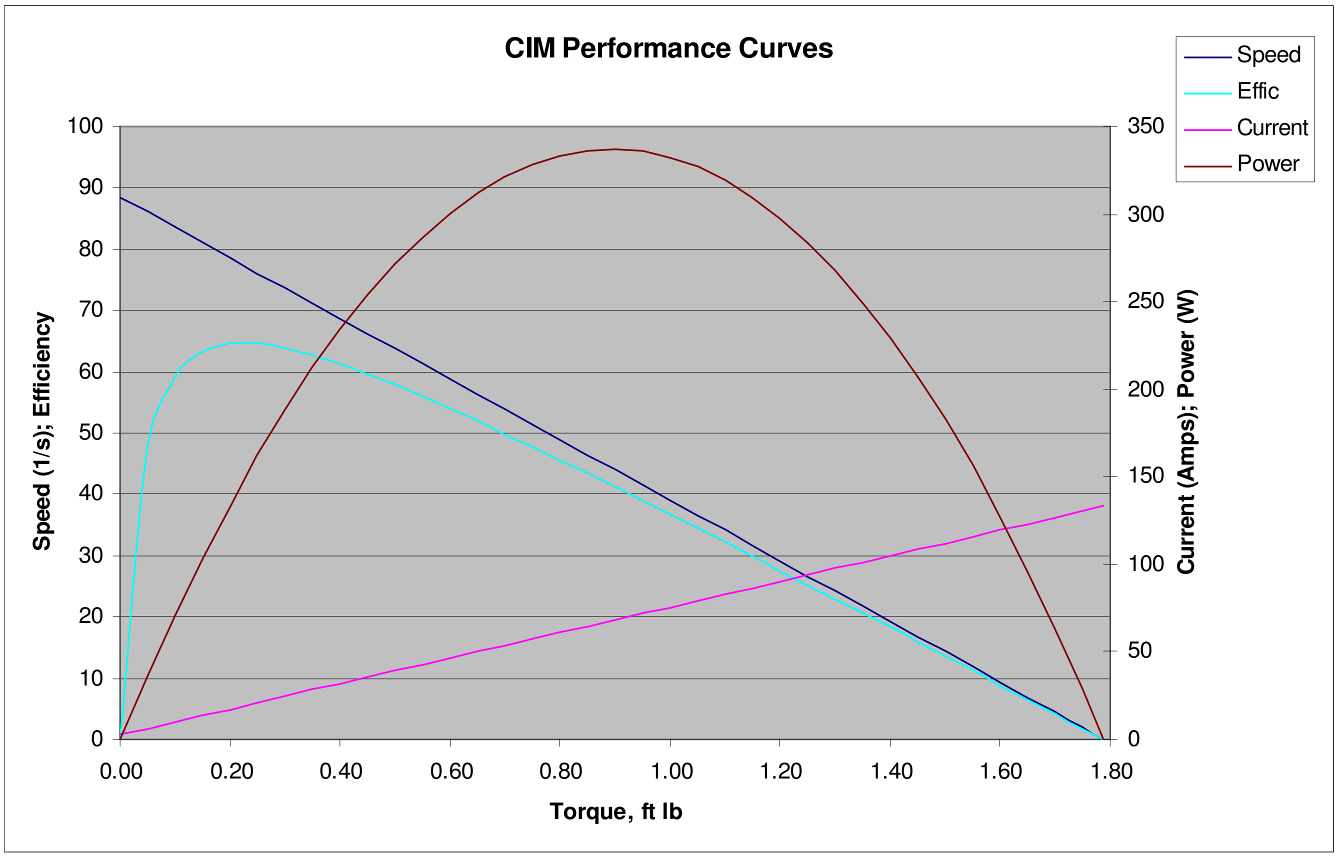


Rotational Speed
Torque

CCL Industrial Motors
(CIM)
FR801-001

Basics - Motors



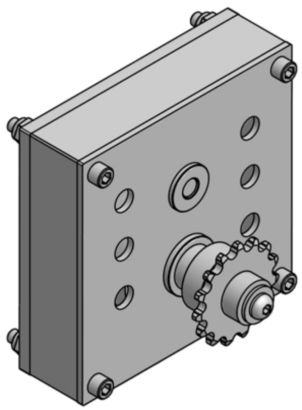


- Motor curve @ 12 V DC
- Allowed a max of (4) CIM Motors on the Robot
- Motors provide power at too low torque and too high speed to be directly useful for driving robot wheels
- Each CIM weighs 2.88 lb

Basics – Transmission

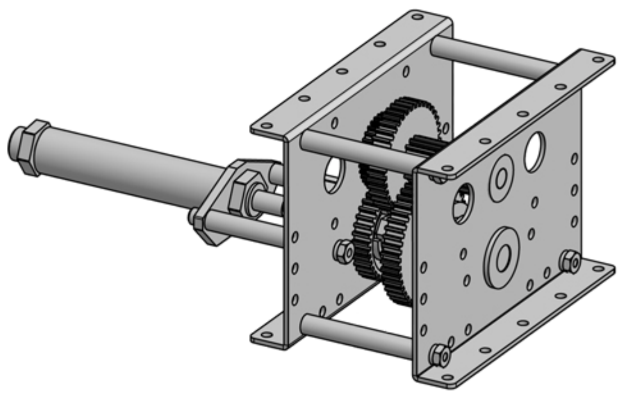
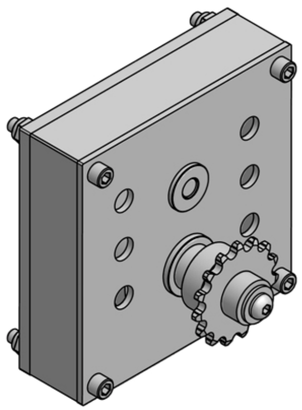
- Transmission
  - Reduces motor rotational speed and increases torque to useful levels to drive wheels
  - Transmits the power to the wheels
  - Optional – it may allow shifting gears to provide more than one effective operating range
    - High gear for speed
    - Low gear for fine control
- May (generally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

Gearbox examples



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

Gearbox examples

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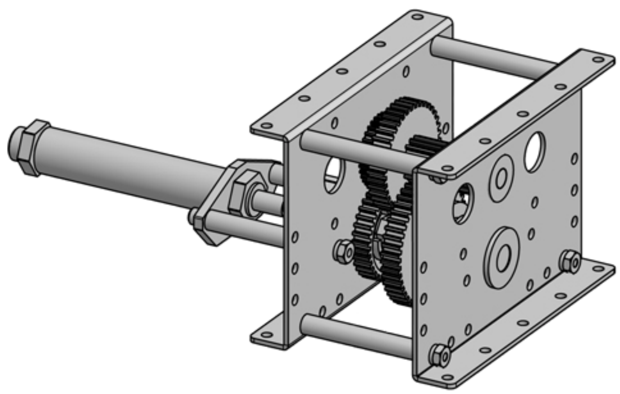
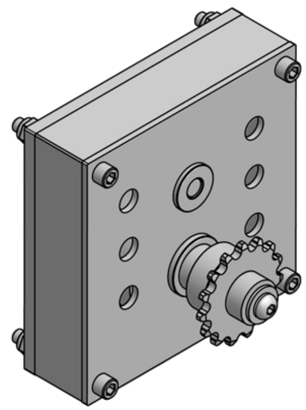
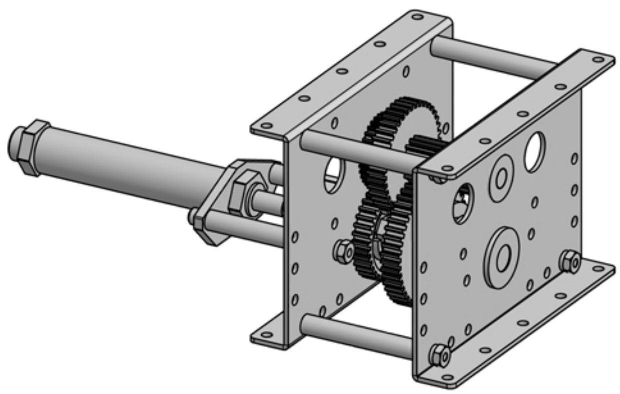
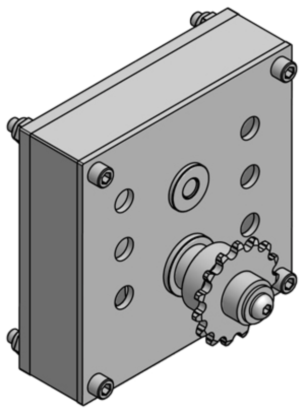


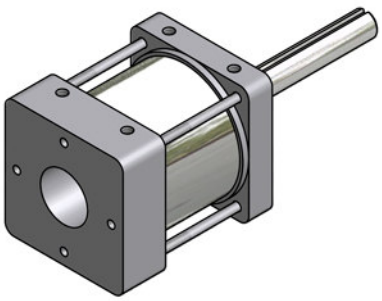


•AndyMark 2-Speed	•AndyMark Toughbox
•10.67:1 and 4.17:1	•5.95:1 or 8.45:1
•Output: 12 tooth sprocket	•Output: ½" keyed shaft
•1 or 2 CIM motors	•1 or 2 CIM motors
•4.14 lb	•2.5 lb
•Used on our previous 2 robots	

Gearbox examples







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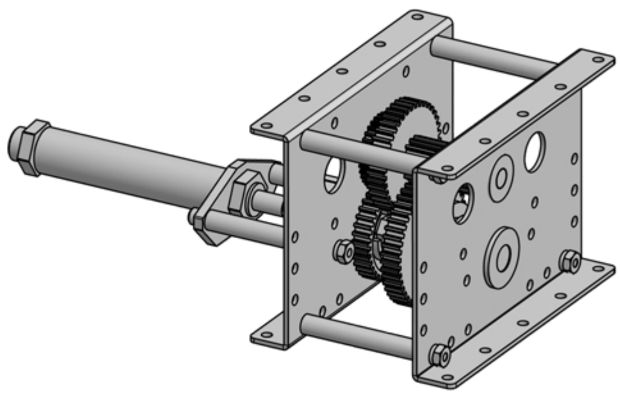

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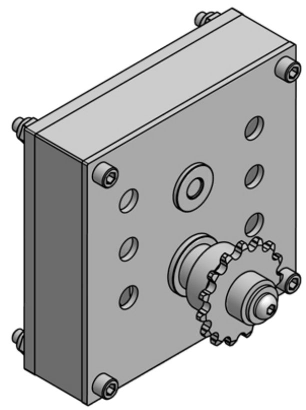

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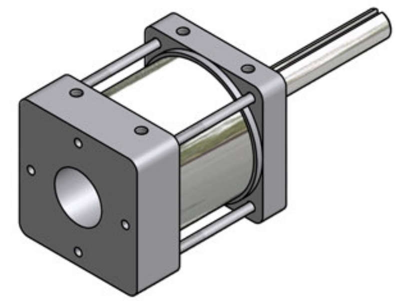
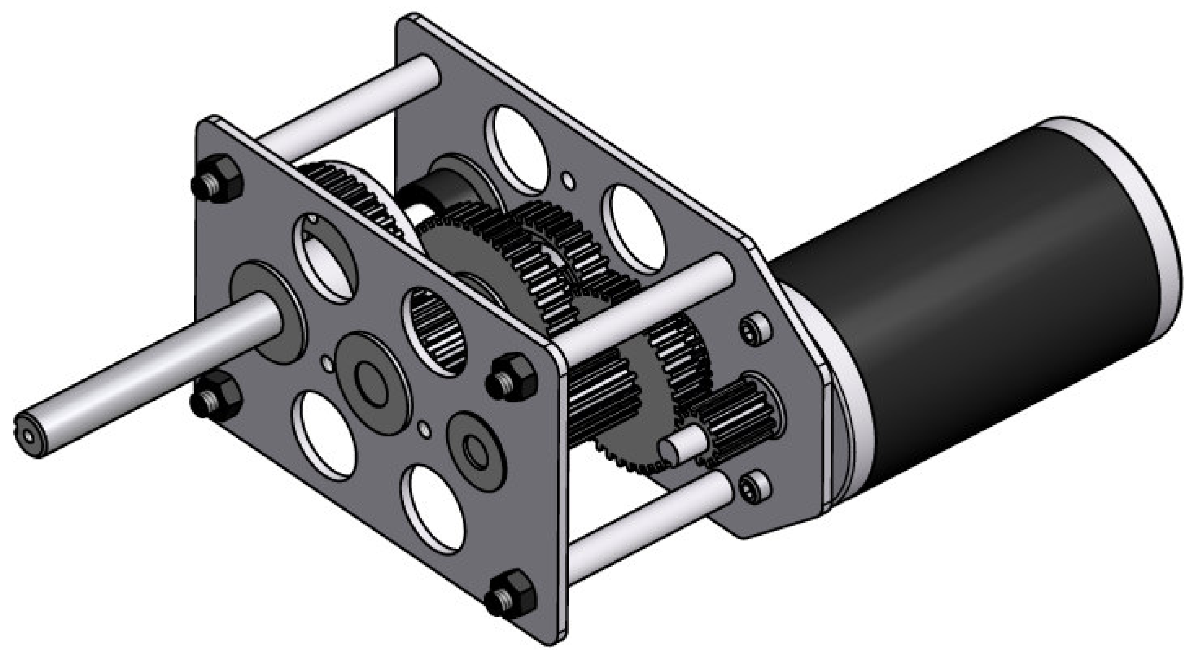


- Bainbots planetary gearbox
- 9:1; 12:1 or 16:1 (2-stage)
- Output – ½″ keyed shaft
- 1 CIM motor (2 available)
- 2.56 lb
- Can drive wheel directly
- 3:1 or 4:1 reduction/stage
- 1 to 4 stages available
- 3:1 to 256:1 available

1640 Custom gearbox

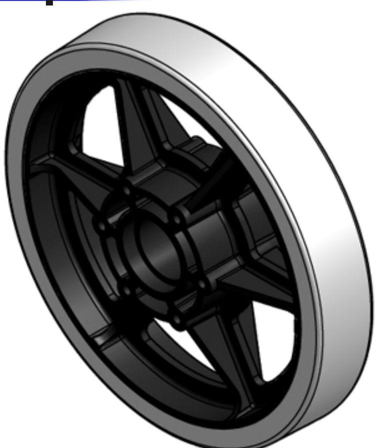
- Modified AndyMark 2-Speed
- Sprocket output replaced w/ 20-tooth gear & additional 45:20 (9:4) reduction added
- Direct-Drive
- ½" shaft output
- 9.4:1 & 24:1
- 1 or 2 CIM motors
- Used successfully on Dewbot V



Power Transmission

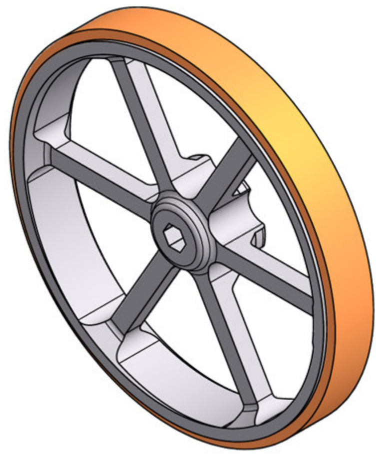
- Chains & Sprockets
  - Traditional
  - Allows further reduction (via sprocket sizing)
  - 3/8" pitch chain
    - Steel – 0.21 lb/ft
    - Polymer – 0.13 lb/ft
- Direct (w/ Bainbots gearbox)
- Gears
- Shafts
- Use your imagination

Basics – Wheels - examples



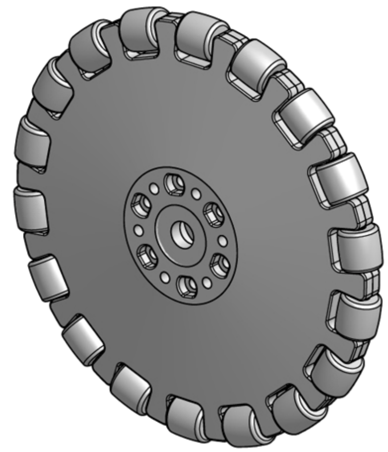
Kit Wheel
6″ diameter

m = 0.48 lb

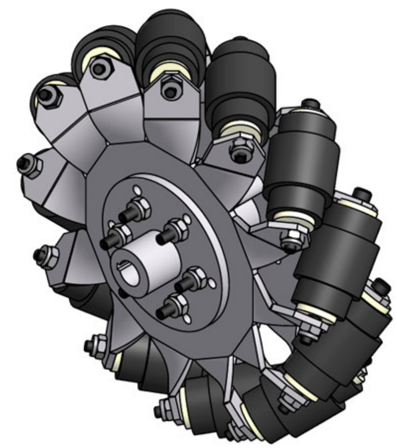


Performance Wheel
8″ diameter
High-traction tread

m = 1.41 lb



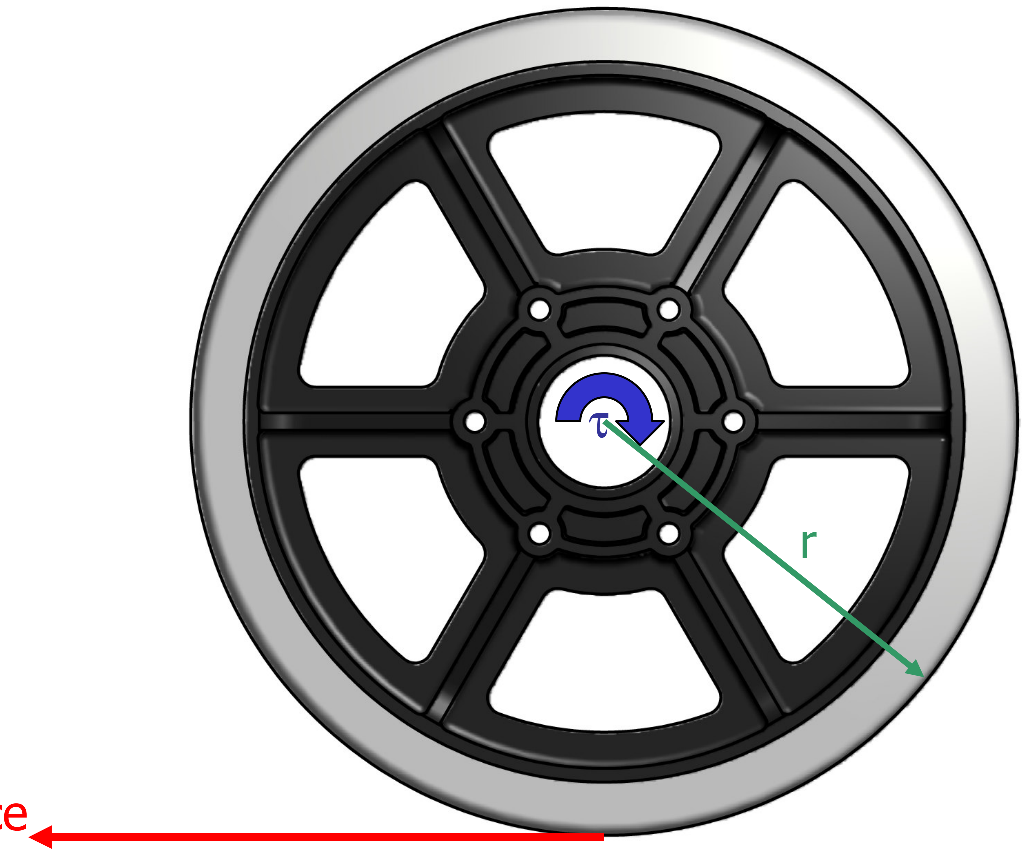
Omni Wheel
8″ diameter
Circumferential rollers
$\mu_{t,s}$ = 1.07
$\mu_{t,k}$ = 0.90
$\mu_{x,s}$ = 0.20
$\mu_{x,k}$ = 0.16
m = 1.13 lb



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

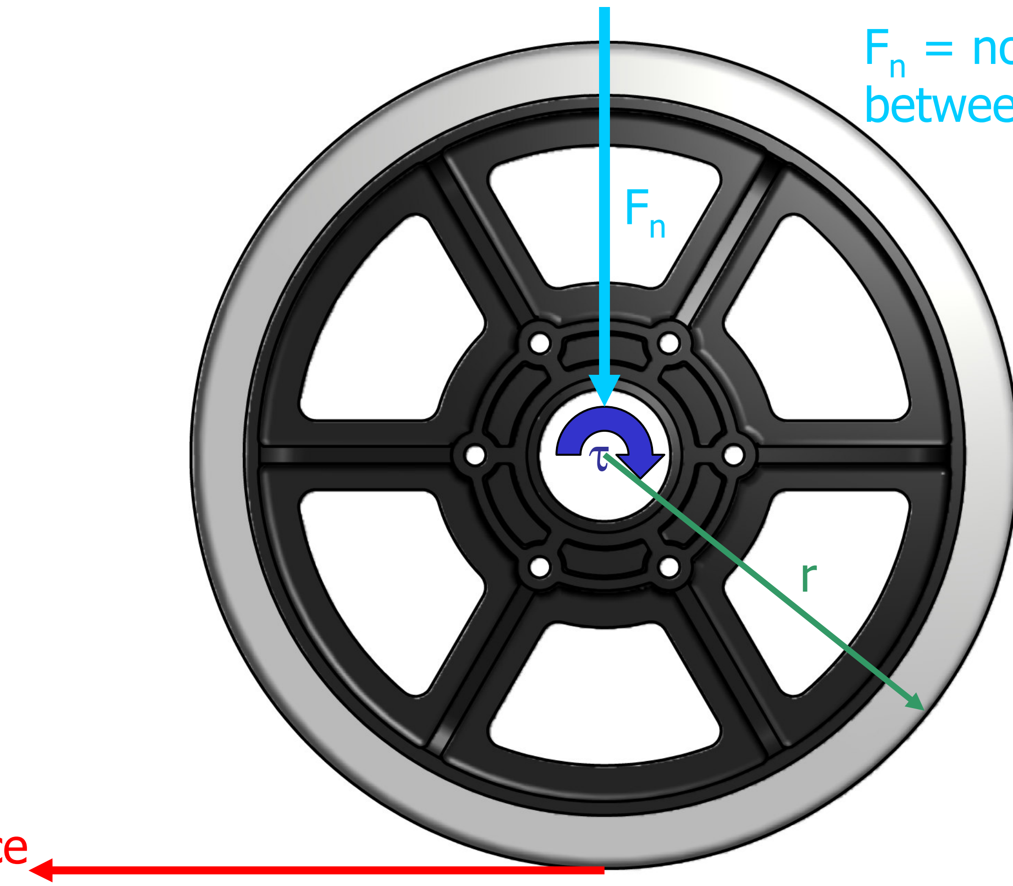
Drive Basics - Propulsion



τ = torque
r = wheel radius

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

Drive Basics - Propulsion



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
$F_d = \tau/r$

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)

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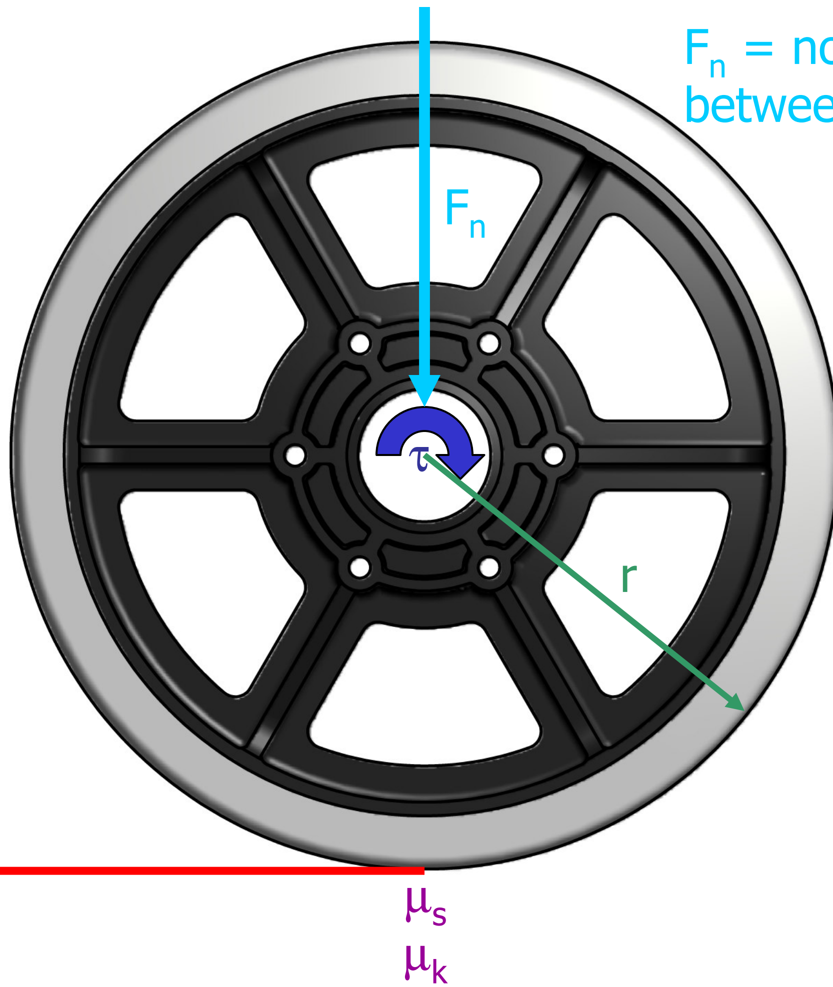

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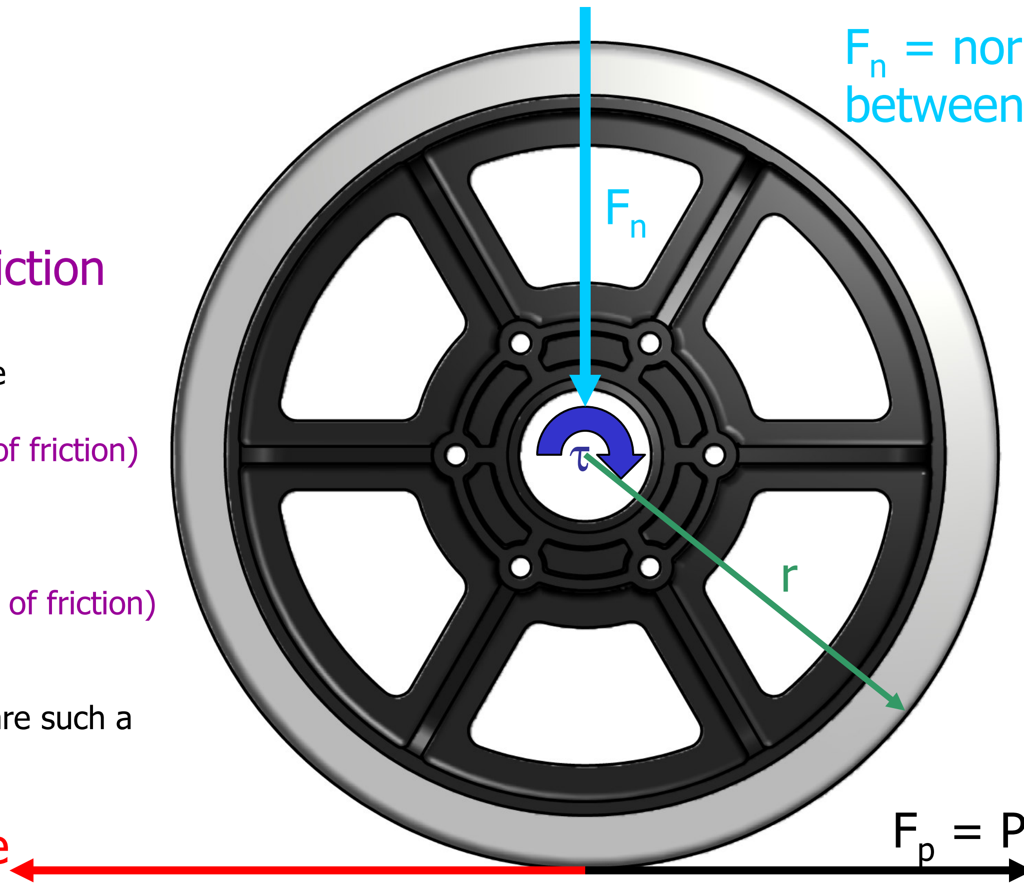

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τ= torque
r = wheel radius

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

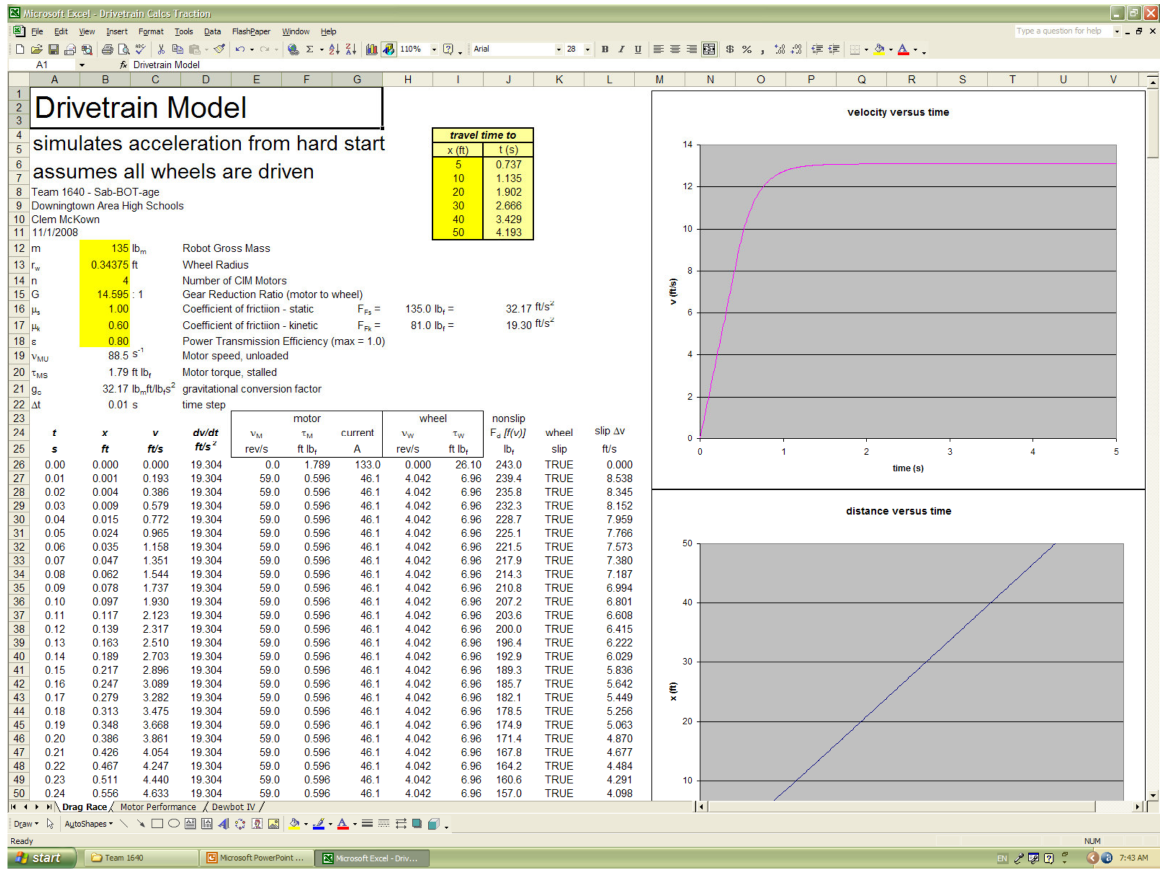
μ_s
μ_k

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: $F_p = F_{f/k}$

Drivetrain Model

$$\frac{dv}{dt} = \frac{n\tau_{ms}\varepsilon G g_c}{m r_w}\left[1 - \frac{G}{2\pi r_w \upsilon_{mu}} v\right]$$

- 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 drivetrain design



Drivetrain Model

simulates acceleration from hard start

assumes all wheels are driven

Team 1640 - Sab-BOT-age

Downingtown Area High Schools

Clem McKown

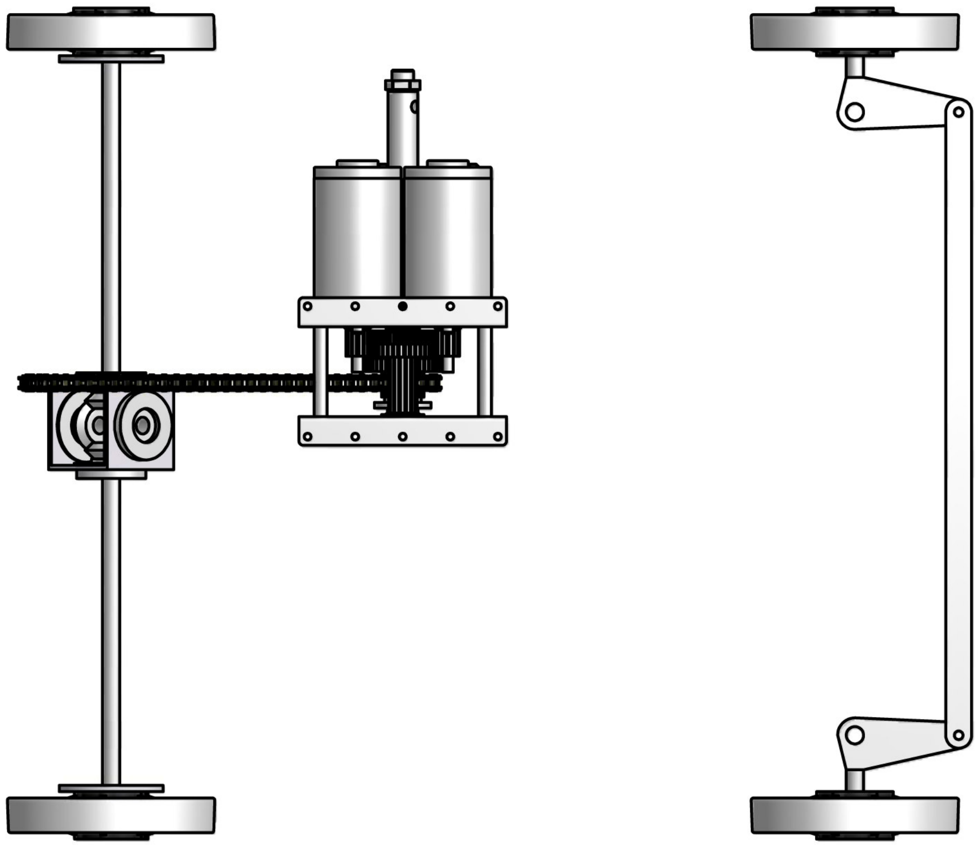
11/1/2008

travel time to	
x (ft)	t (s)
5	0.737
10	1.135
20	1.902
30	2.666
40	3.429
50	4.193

m	135	lb_m	Robot Gross Mass			
r_w	0.34375	ft	Wheel Radius			
n	4		Number of CIM Motors			
G	14.595	: 1	Gear Reduction Ratio (motor to wheel)			
μ_s	1.00		Coefficient of frictiion - static	F_{Fs} =	135.0 lb_f =	32.17 ft/s^2
μ_k	0.60		Coefficient of frictiion - kinetic	F_{Fk} =	81.0 lb_f =	19.30 ft/s^2
ε	0.80		Power Transmission Efficiency (max = 1.0)			
ν_{MU}	88.5	s^{-1}	Motor speed, unloaded			
τ_{MS}	1.79	ft lb_f	Motor torque, stalled			
g_c	32.17	$lb_m ft/lb_f s^2$	gravitational conversion factor			
Δt	0.01	s	time step			

				motor			wheel		nonslip		
t	*x*	*v*	*dv/dt*	ν_M	τ_M	current	ν_W	τ_W	F_d *[f(v)]*	wheel	slip Δv
s	*ft*	*ft/s*	*ft/s^2*	rev/s	ft lb_f	A	rev/s	ft lb_f	lb_f	slip	ft/s
0.00	0.000	0.000	19.304	0.0	1.789	133.0	0.000	26.10	243.0	TRUE	0.000
0.01	0.001	0.193	19.304	59.0	0.596	46.1	4.042	6.96	239.4	TRUE	8.538
0.02	0.004	0.386	19.304	59.0	0.596	46.1	4.042	6.96	235.8	TRUE	8.345
0.03	0.009	0.579	19.304	59.0	0.596	46.1	4.042	6.96	232.3	TRUE	8.152
0.04	0.015	0.772	19.304	59.0	0.596	46.1	4.042	6.96	228.7	TRUE	7.959
0.05	0.024	0.965	19.304	59.0	0.596	46.1	4.042	6.96	225.1	TRUE	7.766
0.06	0.035	1.158	19.304	59.0	0.596	46.1	4.042	6.96	221.5	TRUE	7.573
0.07	0.047	1.351	19.304	59.0	0.596	46.1	4.042	6.96	217.9	TRUE	7.380
0.08	0.062	1.544	19.304	59.0	0.596	46.1	4.042	6.96	214.3	TRUE	7.187
0.09	0.078	1.737	19.304	59.0	0.596	46.1	4.042	6.96	210.8	TRUE	6.994
0.10	0.097	1.930	19.304	59.0	0.596	46.1	4.042	6.96	207.2	TRUE	6.801
0.11	0.117	2.123	19.304	59.0	0.596	46.1	4.042	6.96	203.6	TRUE	6.608
0.12	0.139	2.317	19.304	59.0	0.596	46.1	4.042	6.96	200.0	TRUE	6.415
0.13	0.163	2.510	19.304	59.0	0.596	46.1	4.042	6.96	196.4	TRUE	6.222
0.14	0.189	2.703	19.304	59.0	0.596	46.1	4.042	6.96	192.9	TRUE	6.029
0.15	0.217	2.896	19.304	59.0	0.596	46.1	4.042	6.96	189.3	TRUE	5.836
0.16	0.247	3.089	19.304	59.0	0.596	46.1	4.042	6.96	185.7	TRUE	5.642
0.17	0.279	3.282	19.304	59.0	0.596	46.1	4.042	6.96	182.1	TRUE	5.449
0.18	0.313	3.475	19.304	59.0	0.596	46.1	4.042	6.96	178.5	TRUE	5.256
0.19	0.348	3.668	19.304	59.0	0.596	46.1	4.042	6.96	174.9	TRUE	5.063
0.20	0.386	3.861	19.304	59.0	0.596	46.1	4.042	6.96	171.4	TRUE	4.870
0.21	0.426	4.054	19.304	59.0	0.596	46.1	4.042	6.96	167.8	TRUE	4.677
0.22	0.467	4.247	19.304	59.0	0.596	46.1	4.042	6.96	164.2	TRUE	4.484
0.23	0.511	4.440	19.304	59.0	0.596	46.1	4.042	6.96	160.6	TRUE	4.291
0.24	0.556	4.633	19.304	59.0	0.596	46.1	4.042	6.96	157.0	TRUE	4.098

How an automobile drives



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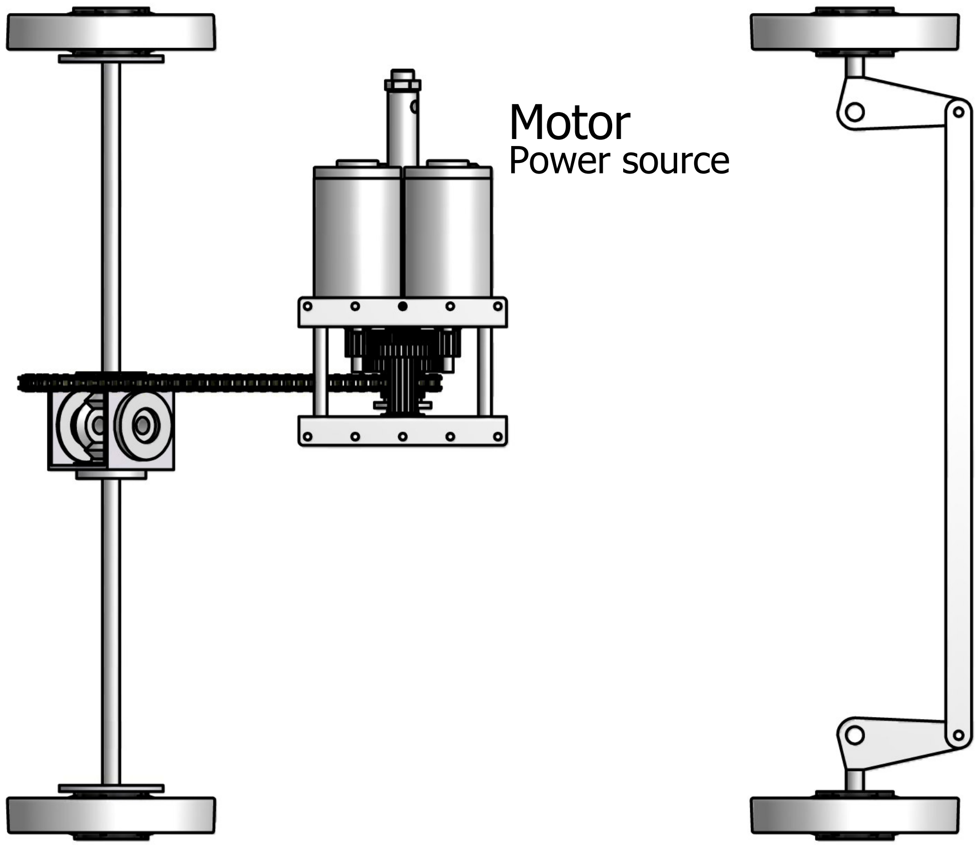

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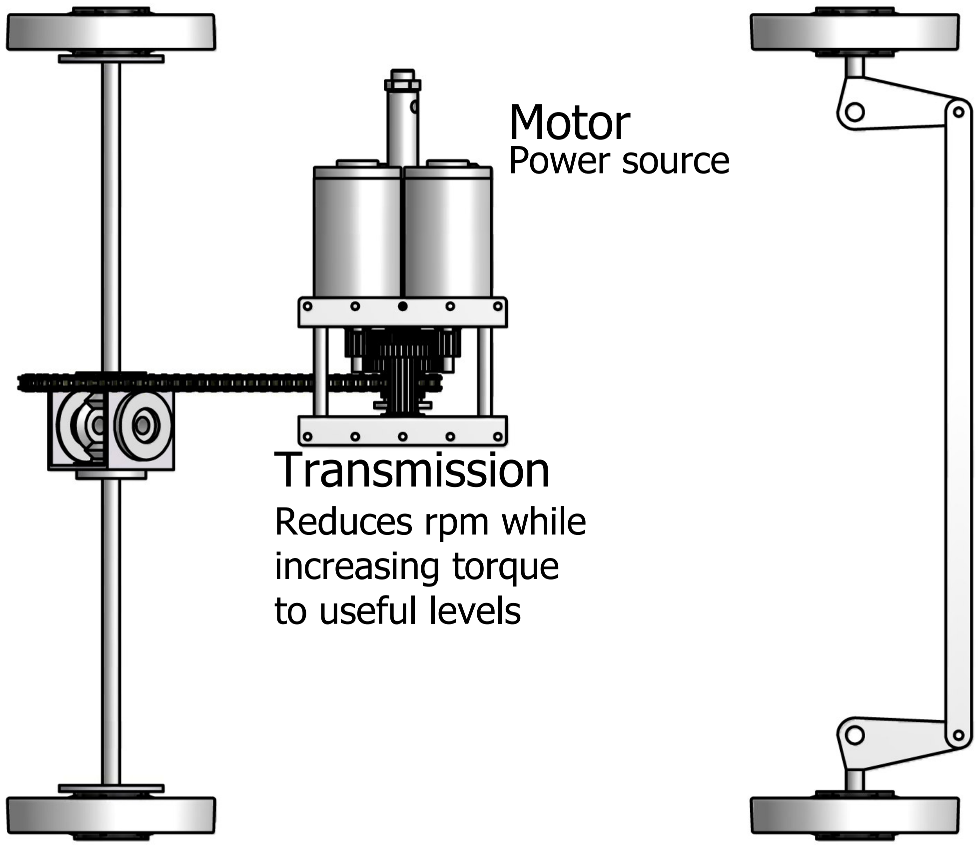

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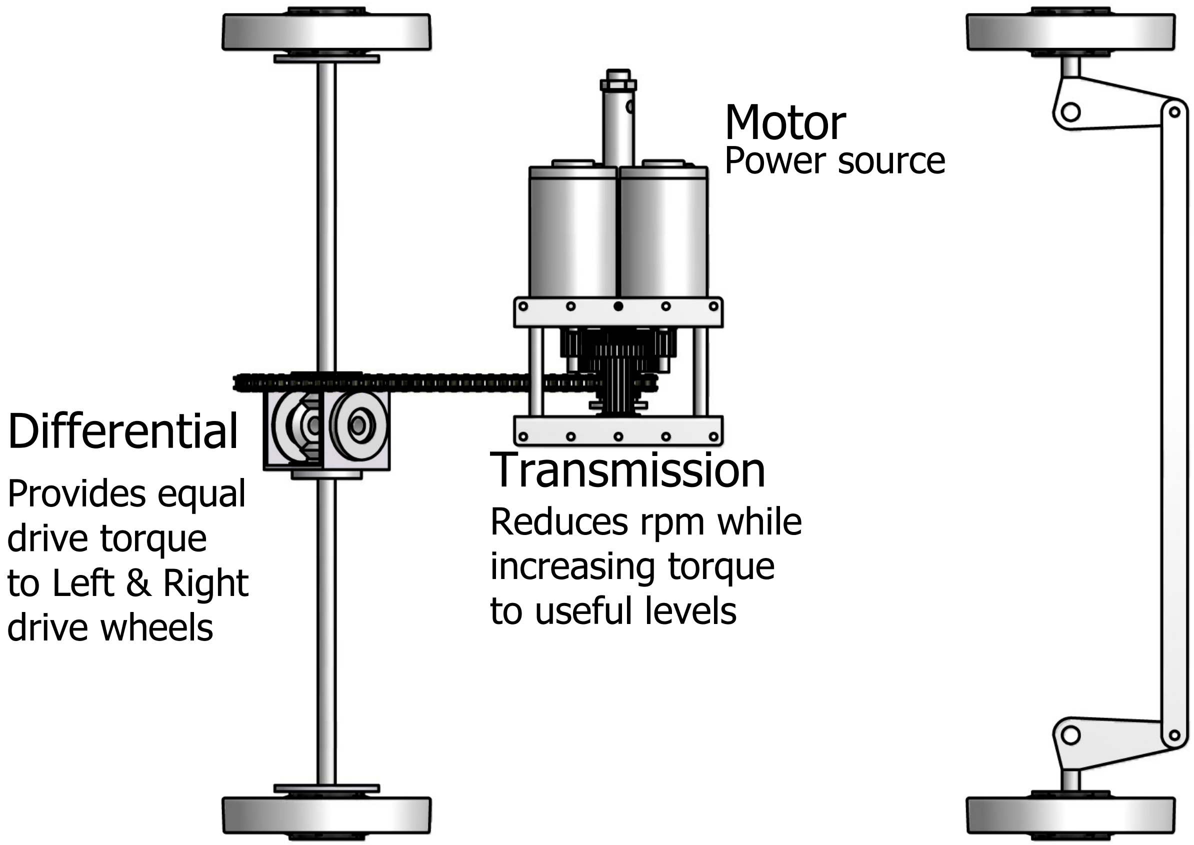

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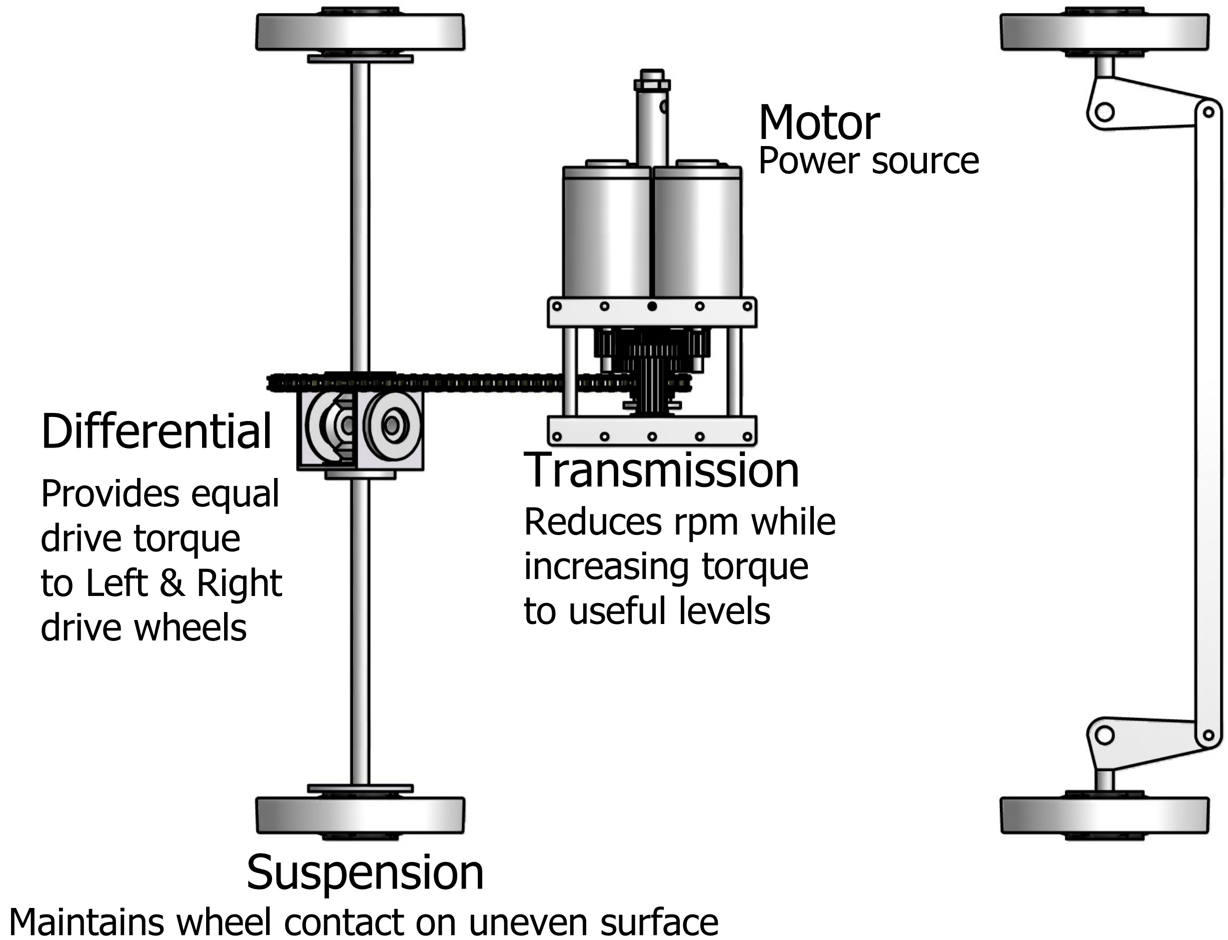

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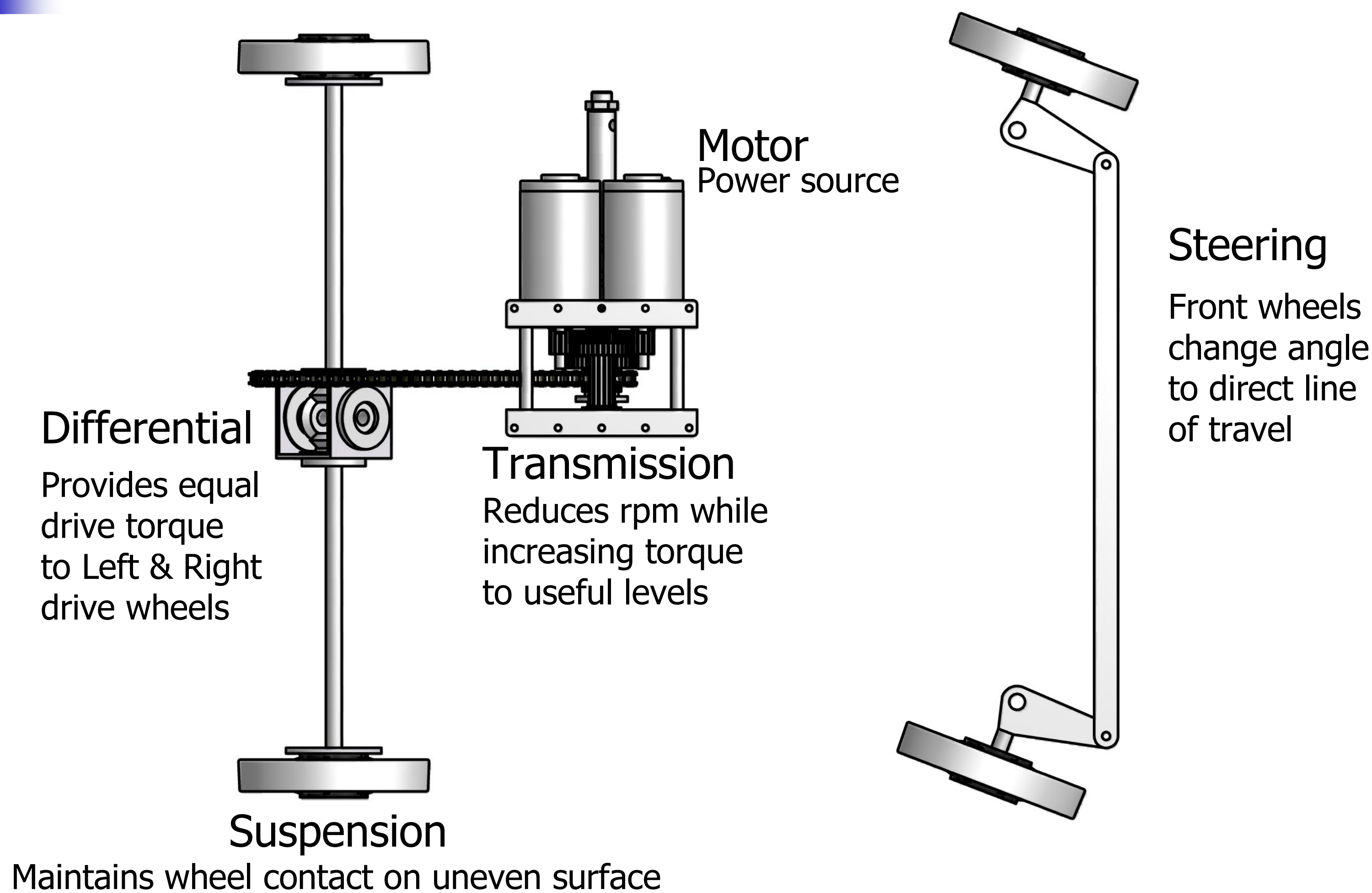
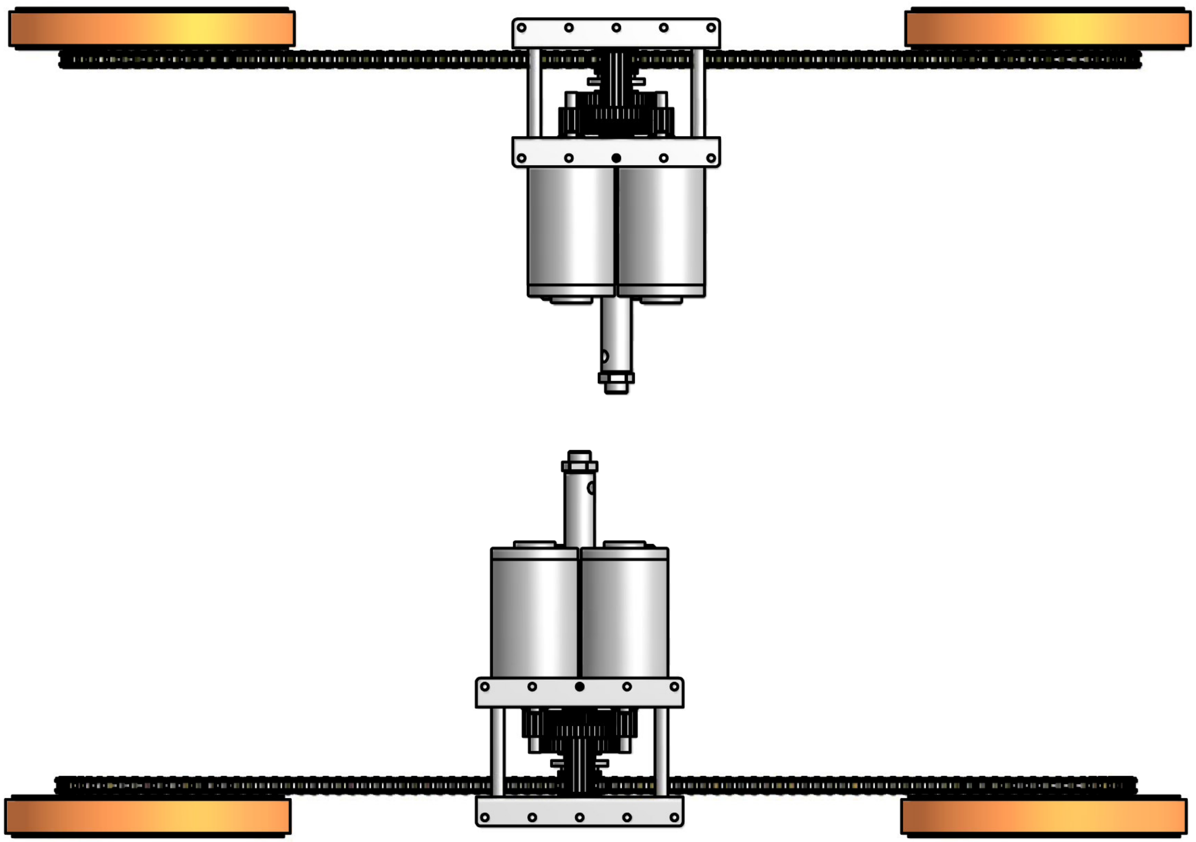


How a (typical) robot drives



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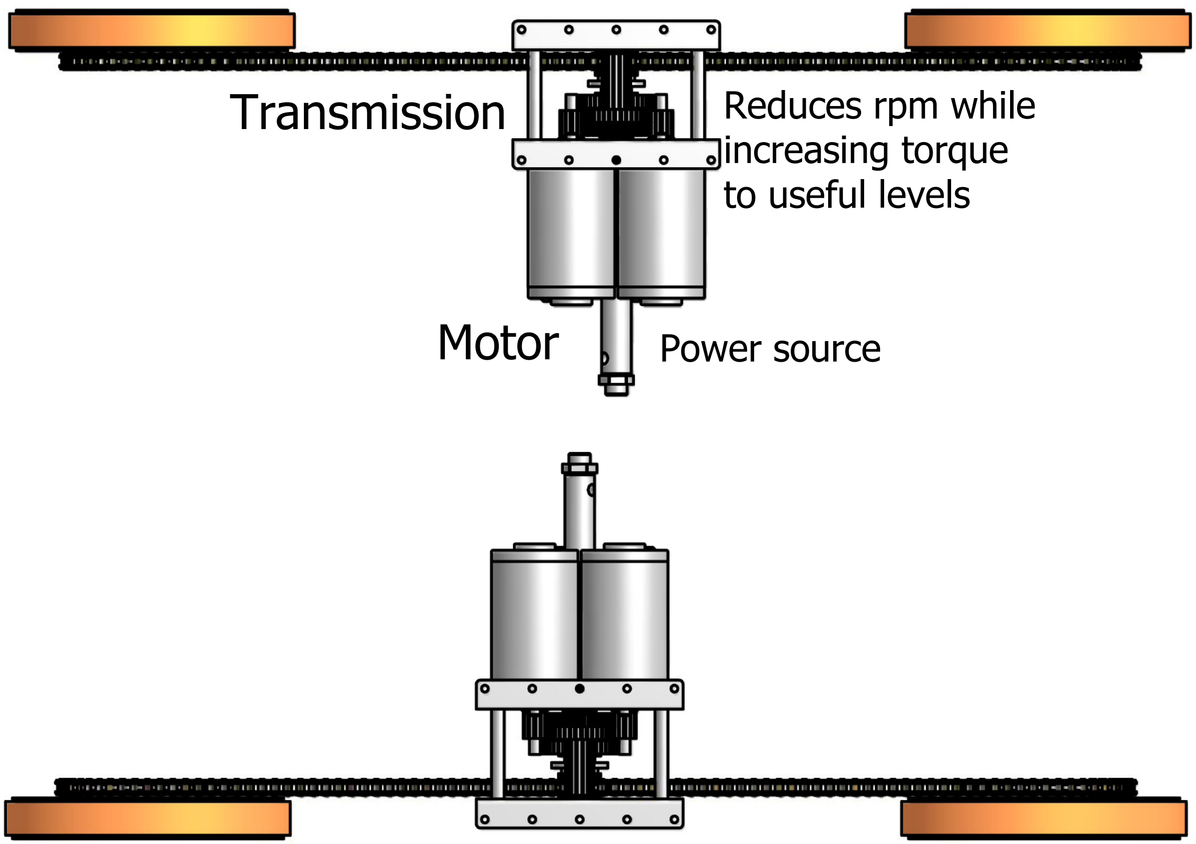

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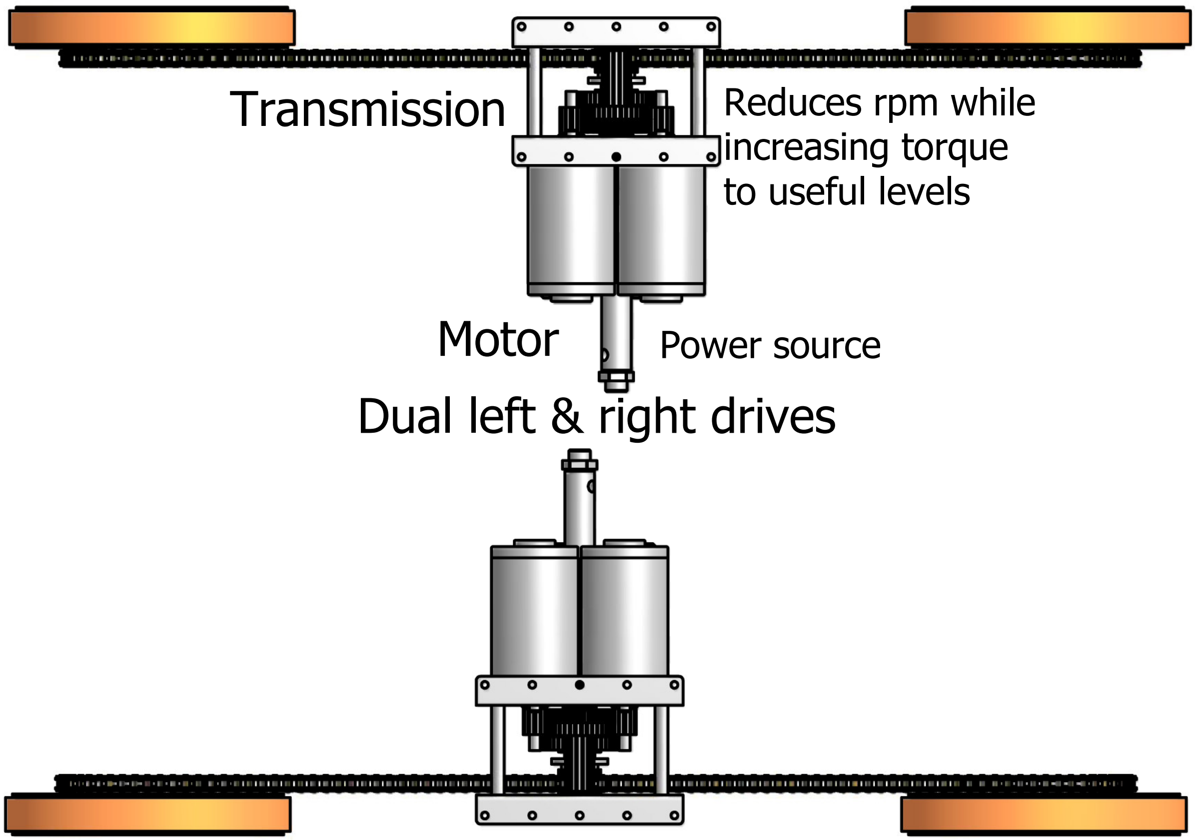

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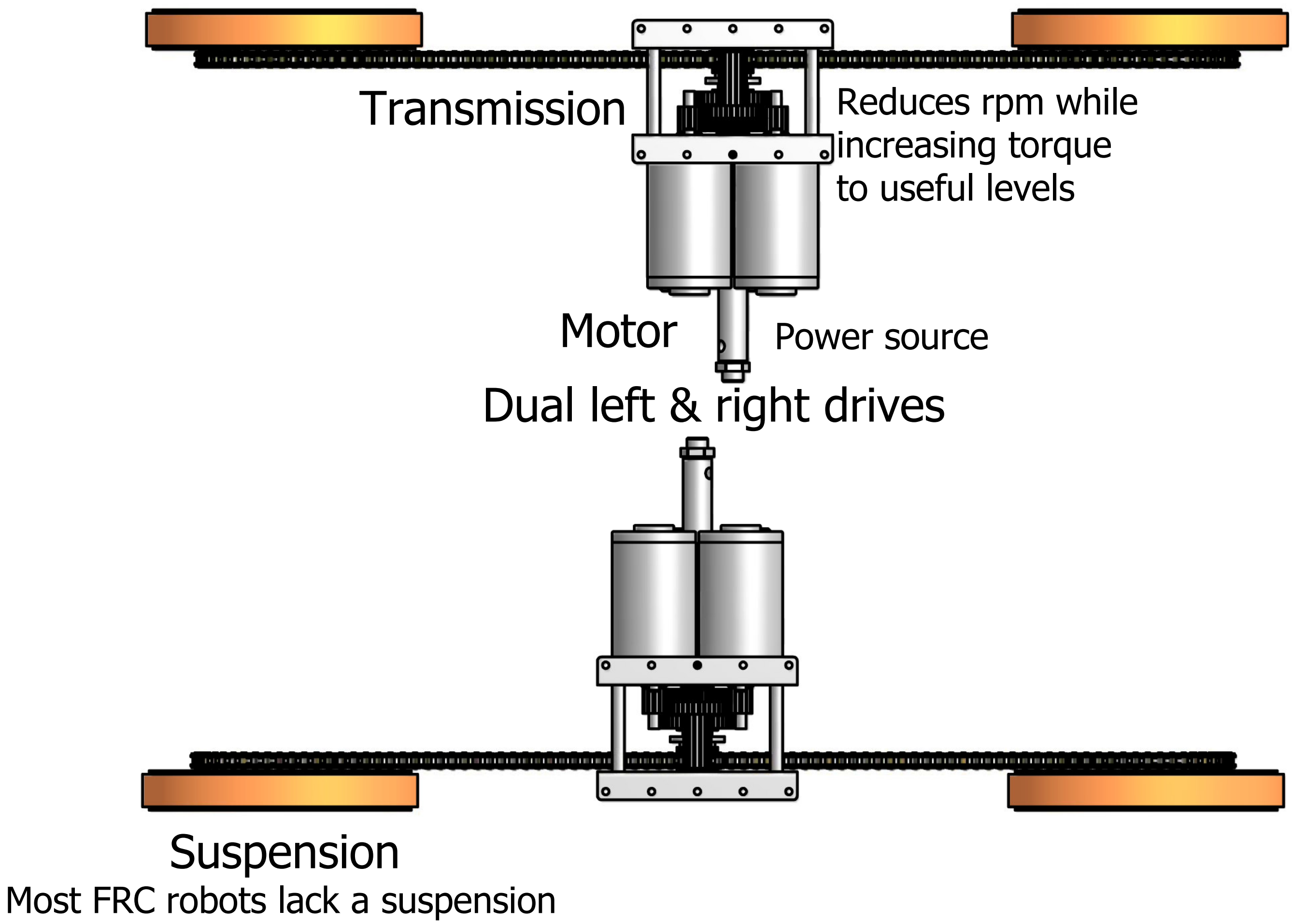

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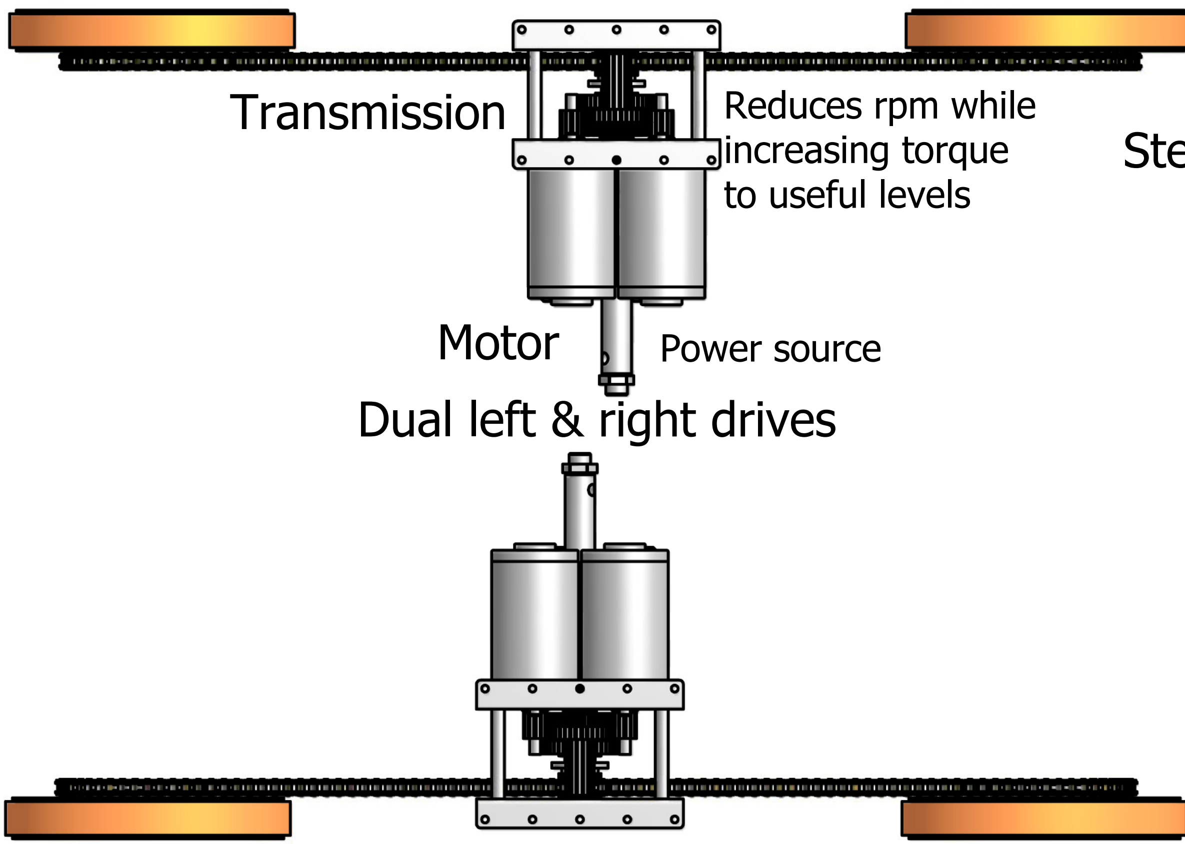

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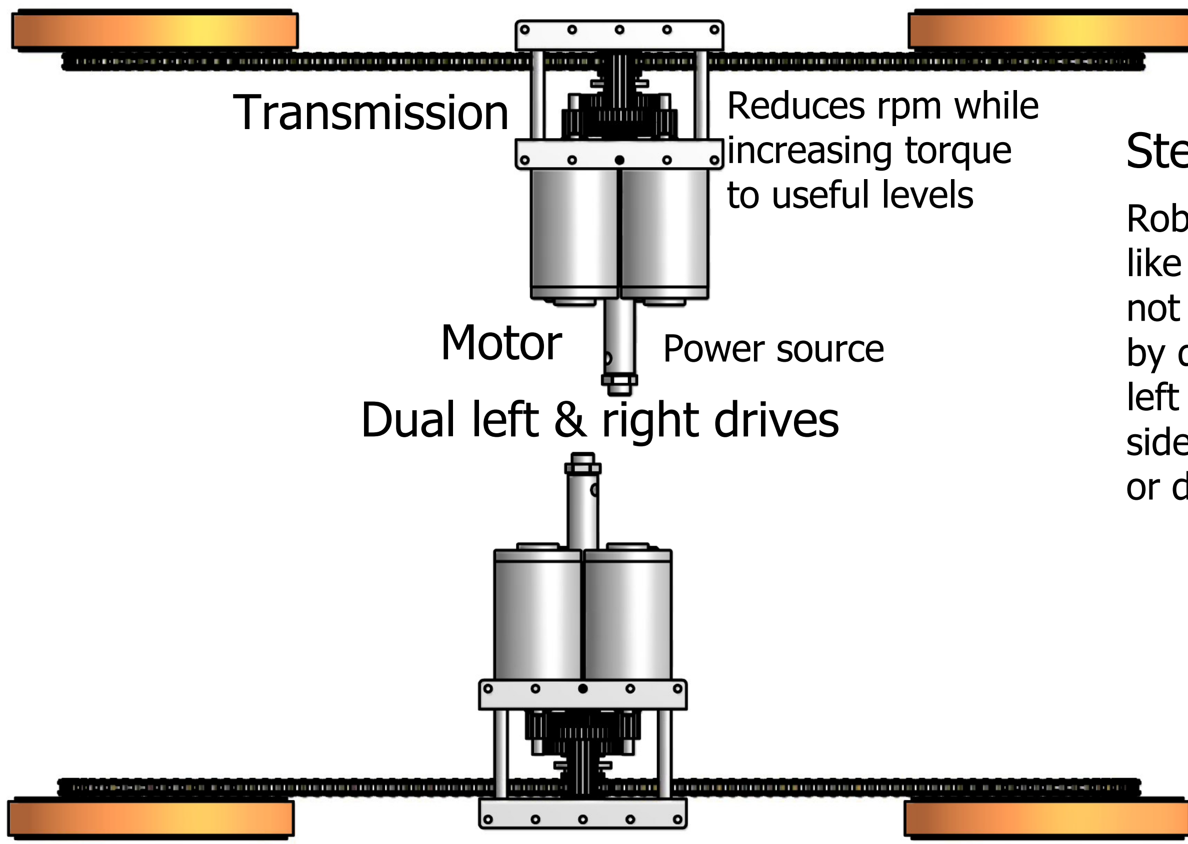


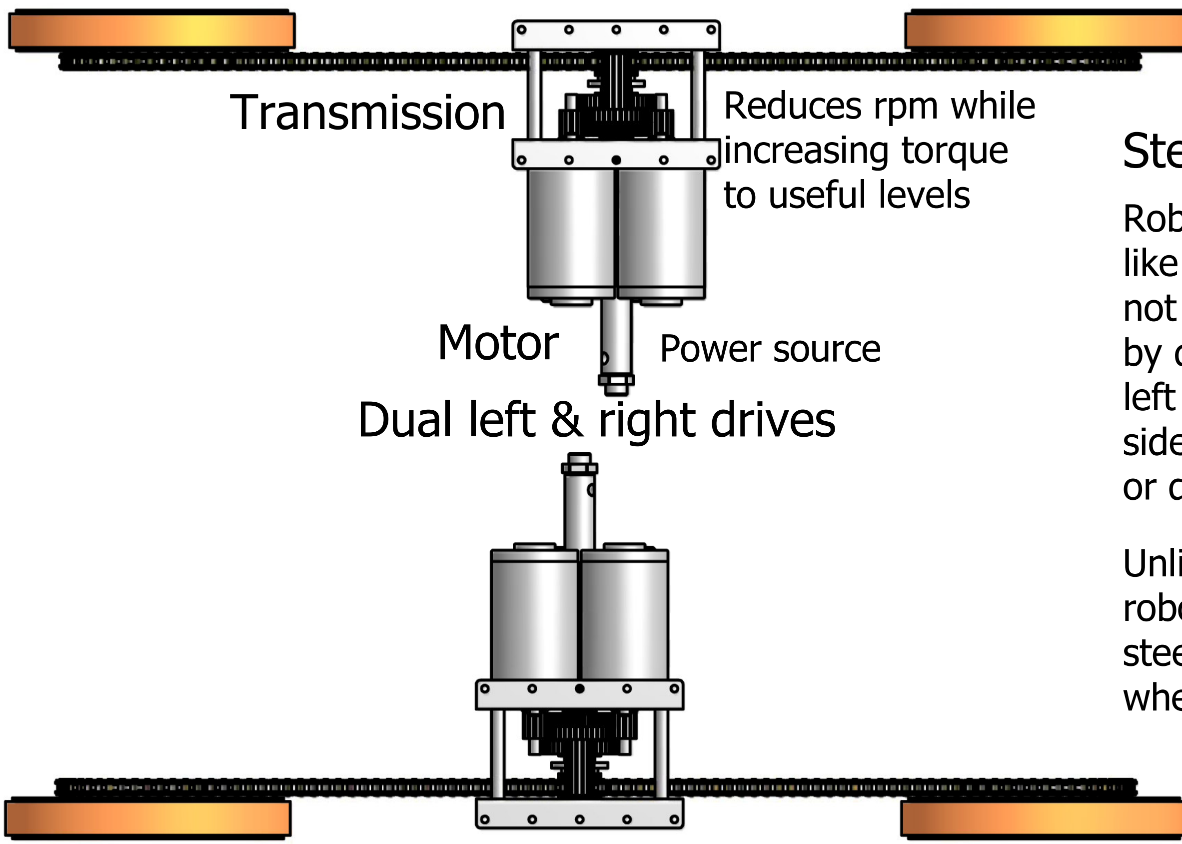
Steering

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

Suspension

Most FRC robots lack a suspension

How a (typical) robot drives



Suspension
Most FRC robots lack a suspension

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

Car - Robot Comparison

Automobile Drive
+ Efficient steering

Robot (Tank) Drive
- High energy steering

Car - Robot Comparison

Automobile Drive

+ Efficient steering
+ Smooth steering

Robot (Tank) Drive

- High energy steering
- Steering hysterisis

Car - Robot Comparison

Automobile Drive

+ Efficient steering
+ Smooth steering
+ Avoids wheel sliding

Robot (Tank) Drive

- High energy steering
- Steering hysterisis
- Wheels slide to turn

Car - Robot Comparison

Automobile Drive

+ Efficient steering
+ Smooth steering
+ Avoids wheel sliding
+ Low wheel wear

Robot (Tank) Drive

- High energy steering
- Steering hysterisis
- Wheels slide to turn
- High wheel wear

Car - Robot Comparison

Automobile Drive

- \+ Efficient steering
- \+ Smooth steering
- \+ Avoids wheel sliding
- \+ Low wheel wear
- \- Large turn radius
- \- Cannot turn in place

Robot (Tank) Drive

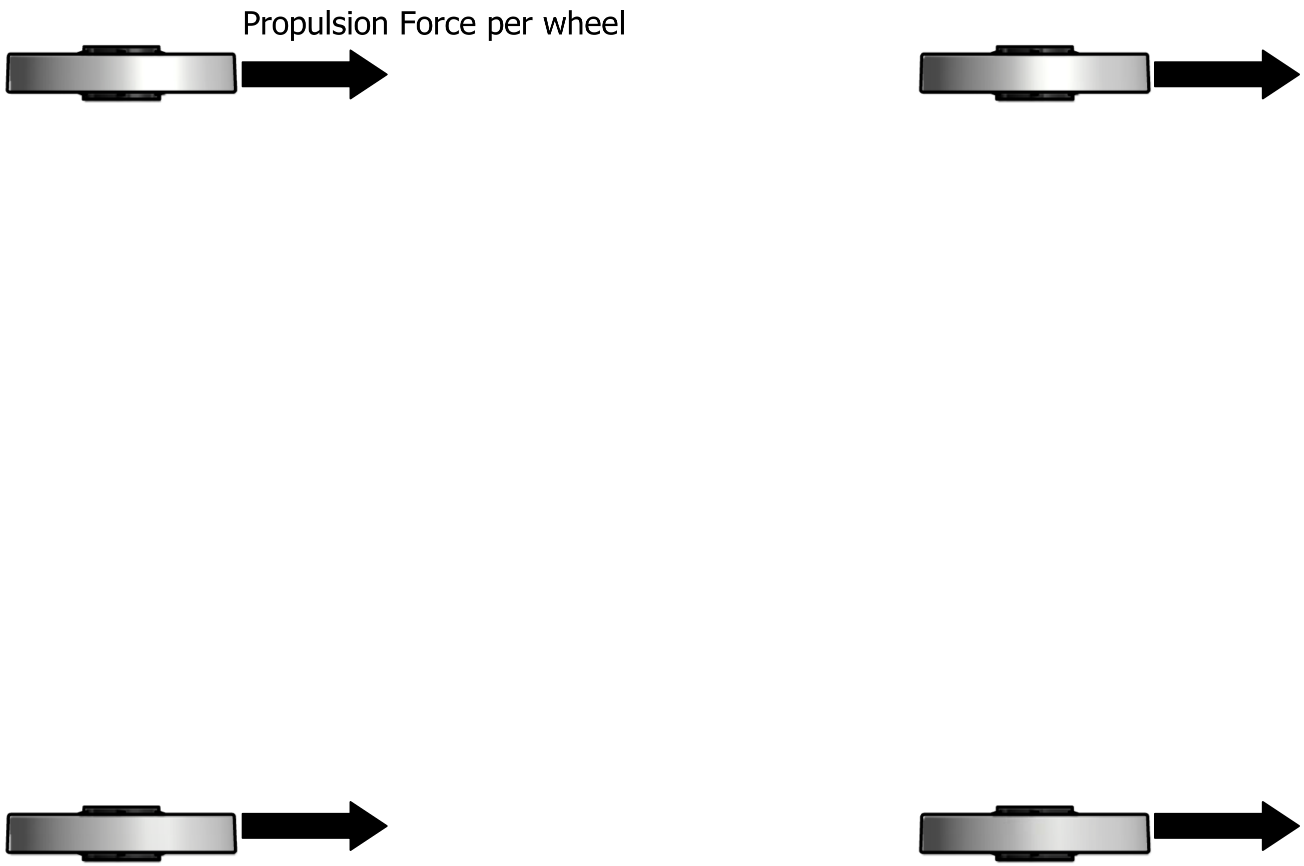
- \- High energy steering
- \- Steering hysterisis
- \- Wheels slide to turn
- \- High wheel wear
- \+ Zero turning radius
- \+ Turns in place

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

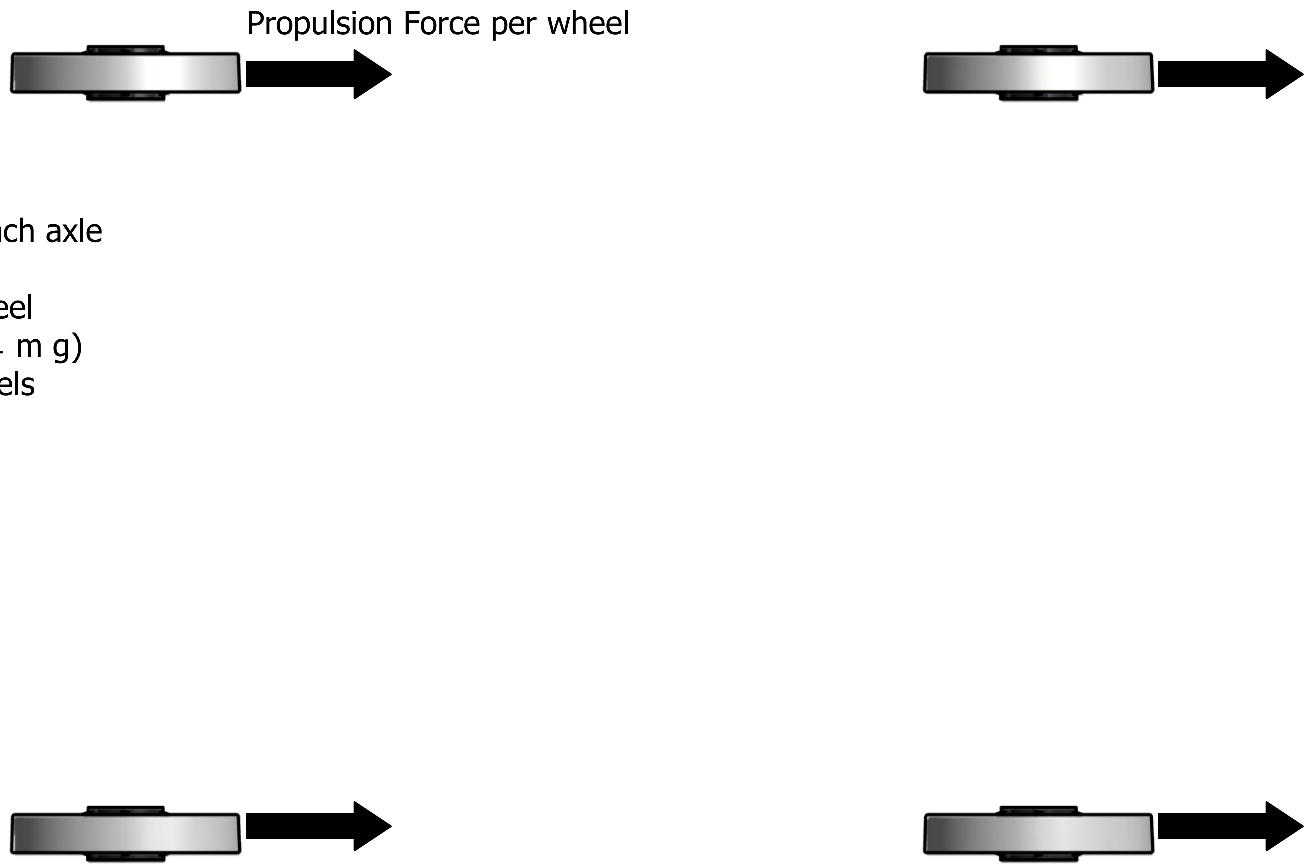
Propulsion Force (F_p) – Symmetric 4wd



Propulsion Force (F_p) – Symmetric 4wd

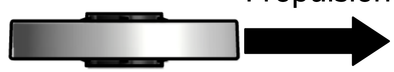
Assumptions / Variables:

- 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



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:

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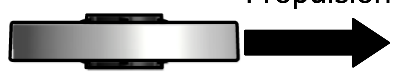

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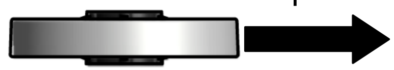
Robot Propulsion Force

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

Propulsion Force (F_p) – Symmetric 4wd



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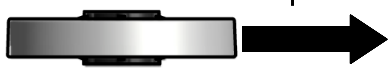
Robot Propulsion Force

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

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

Propulsion Force (F_p) – Symmetric 4wd

Propulsion Force per wheel



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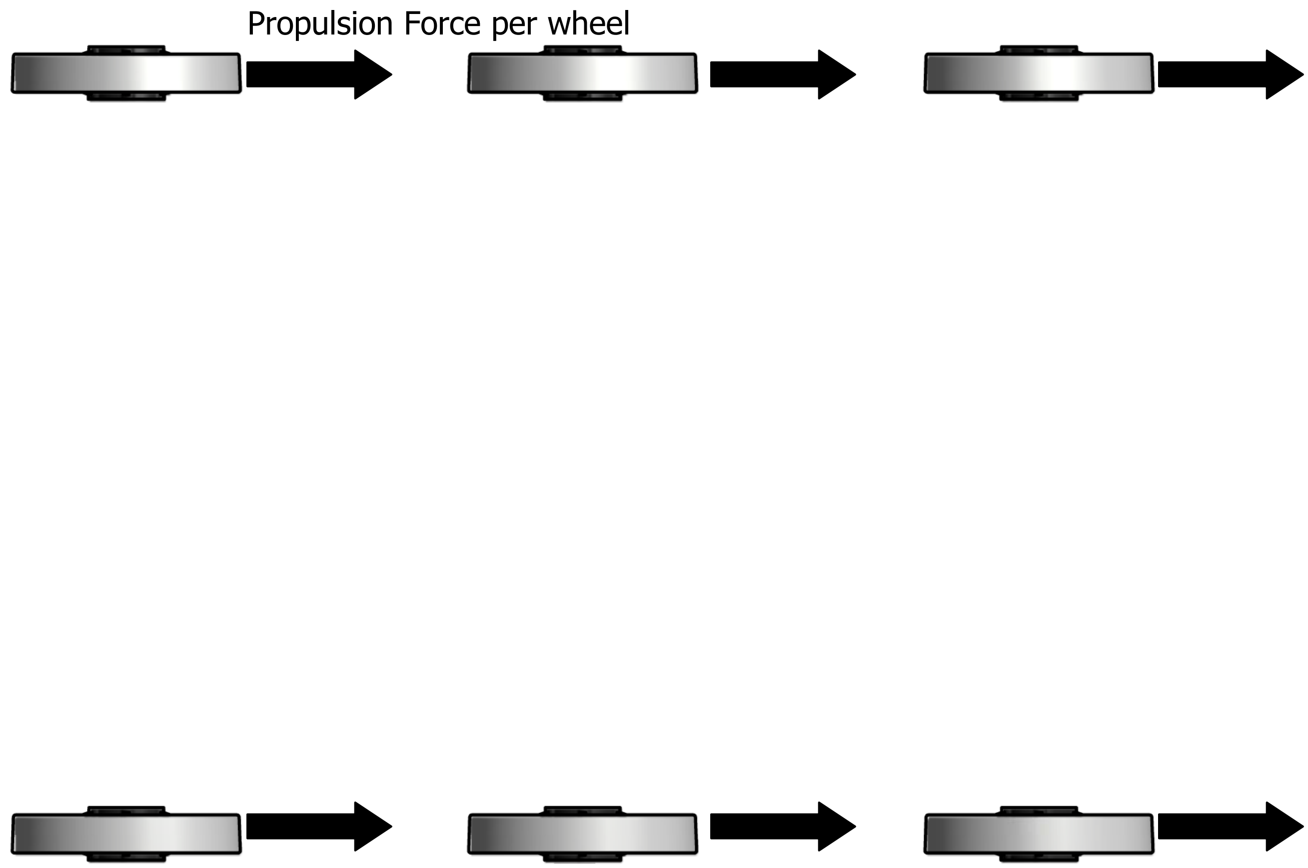
Rolling without slipping: $F_{p/R} = 4\tau/r_w$

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

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

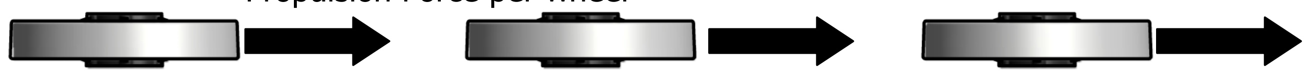
(SI): $F_{p/R} = \mu_k m g$

F_p – Symmetric 6wd



F_p – Symmetric 6wd

Propulsion Force per wheel



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F_p – Symmetric 6wd

Propulsion Force per wheel

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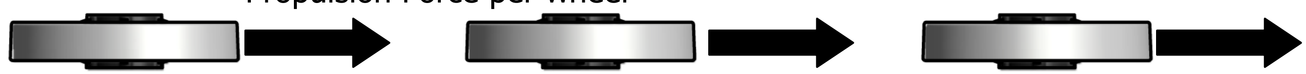
F_p – Symmetric 6wd

Propulsion Force per wheel



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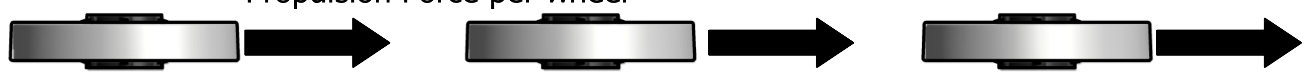
F_p – Symmetric 6wd

Propulsion Force per wheel



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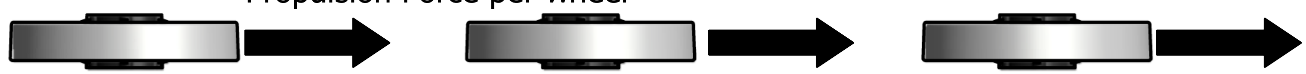
Robot Propulsion Force

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

Rolling without slipping: $F_{p/R} = 6\ {}^2/_3\tau/r_w = 4\tau/r_w$

F_p – Symmetric 6wd

Propulsion Force per wheel



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Robot Propulsion Force

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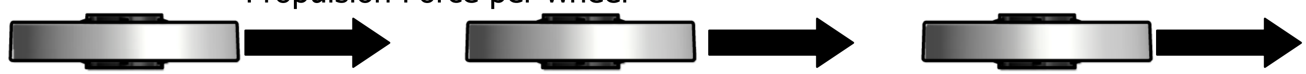
F_p – Symmetric 6wd

Propulsion Force per wheel



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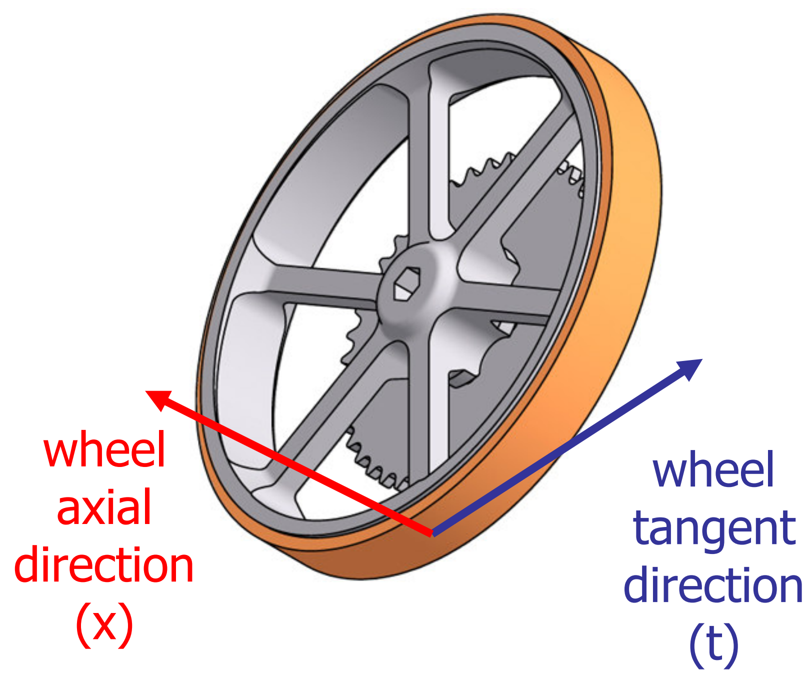
(SI): $F_{p/R} = \mu_k\, m\, g$

<u>Conclusion</u>

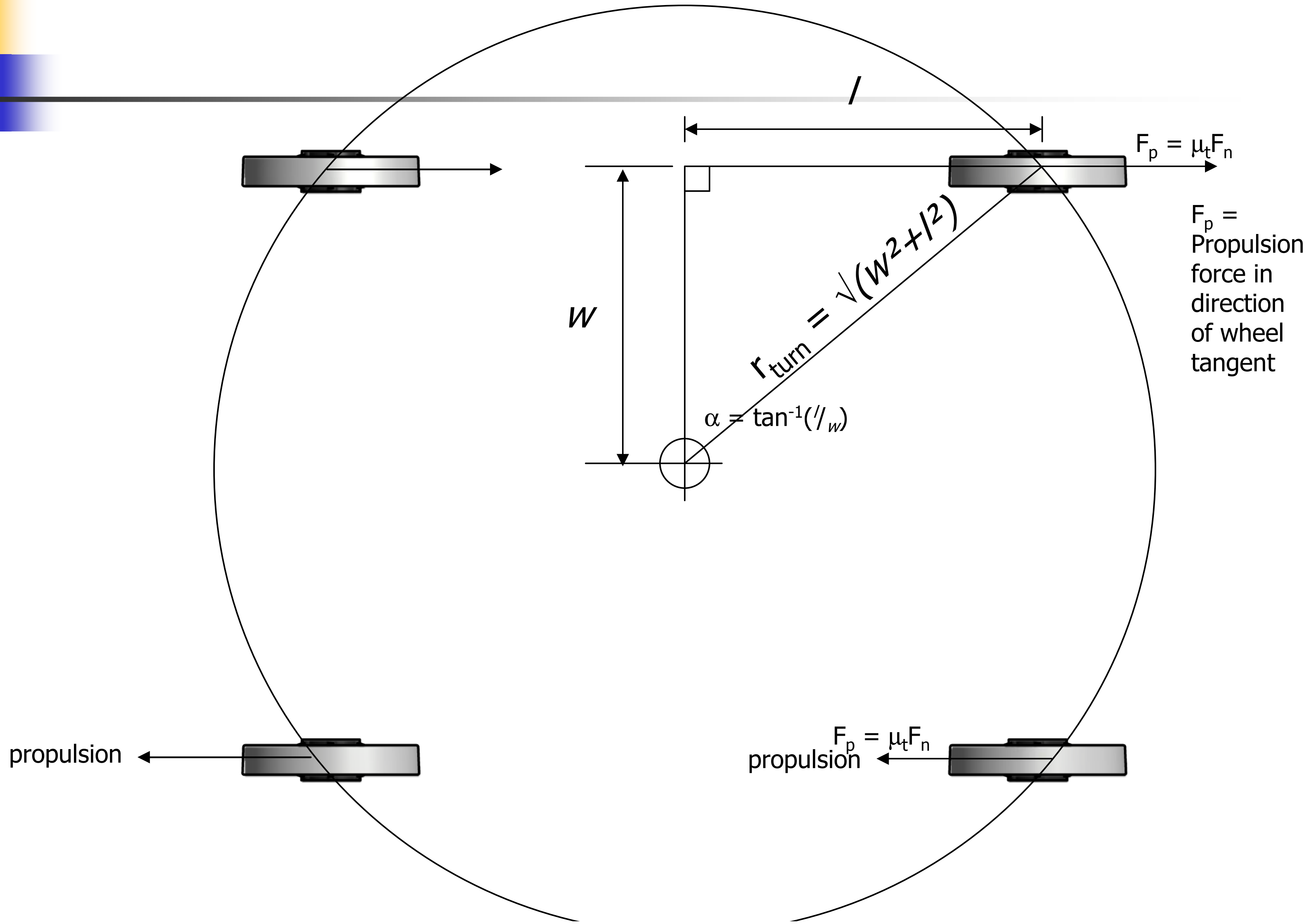
Would not expect 6wd to provide any benefit in propulsion (or pushing) vis-à-vis 4wd (all other factors being equal)

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



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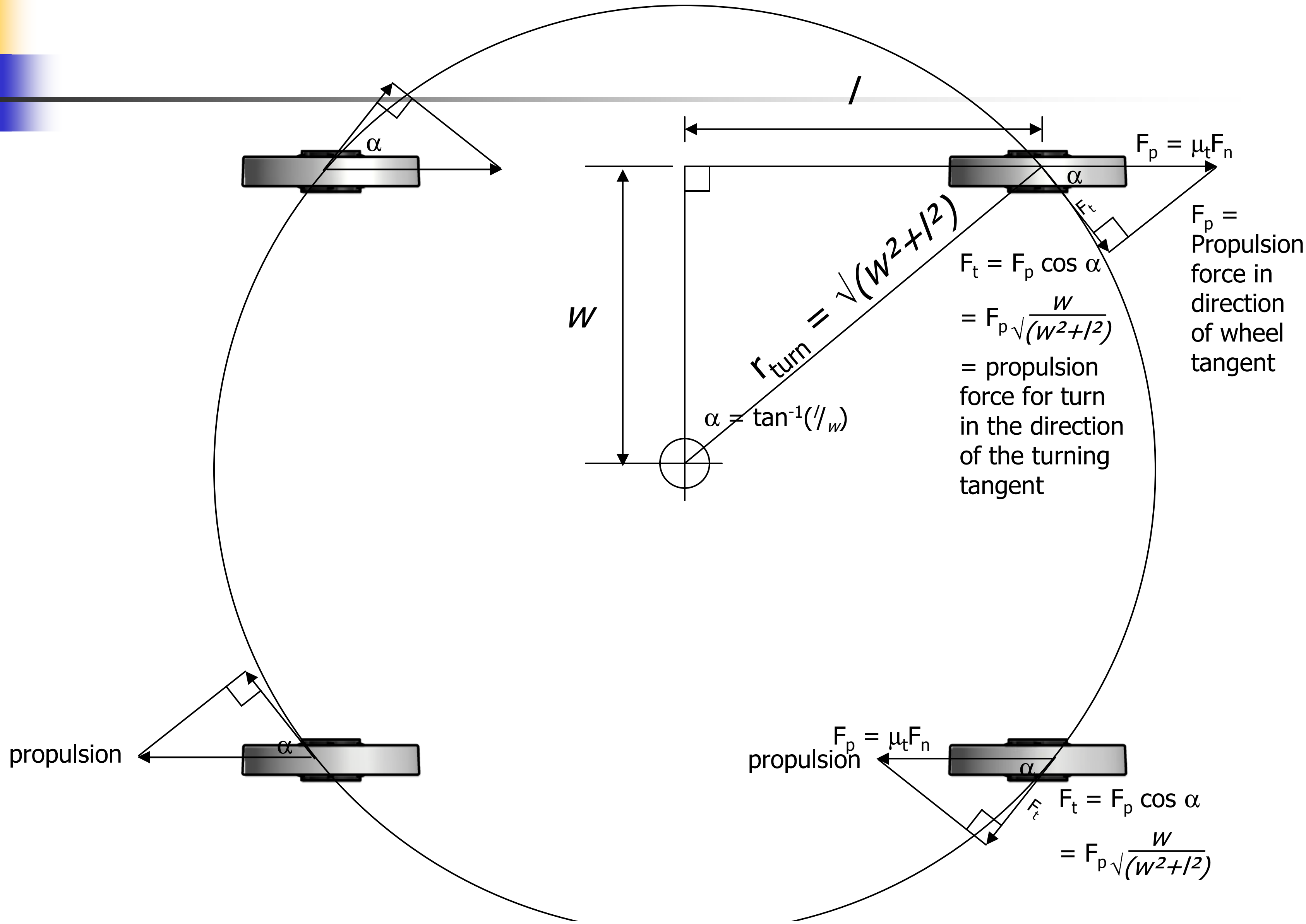

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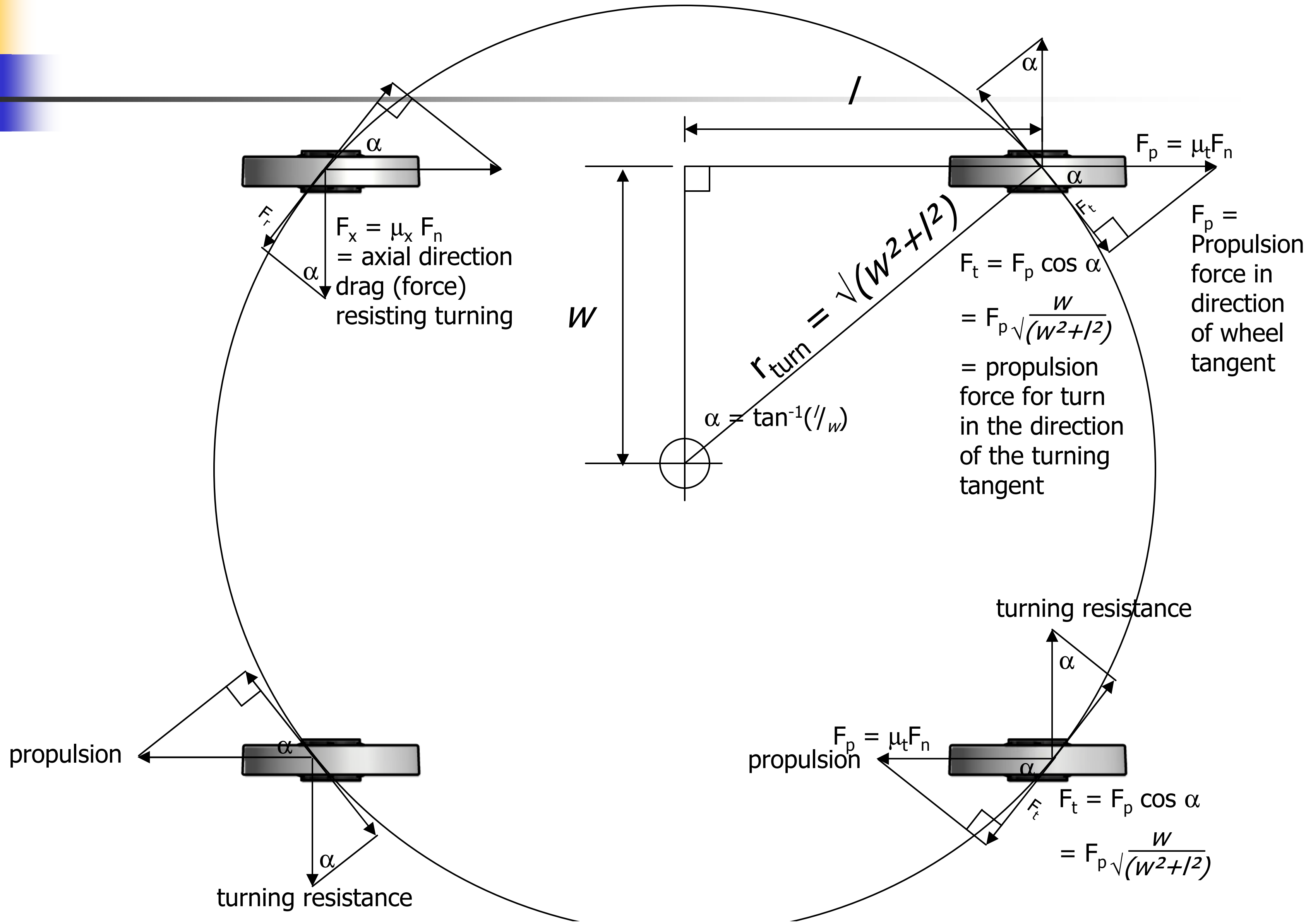

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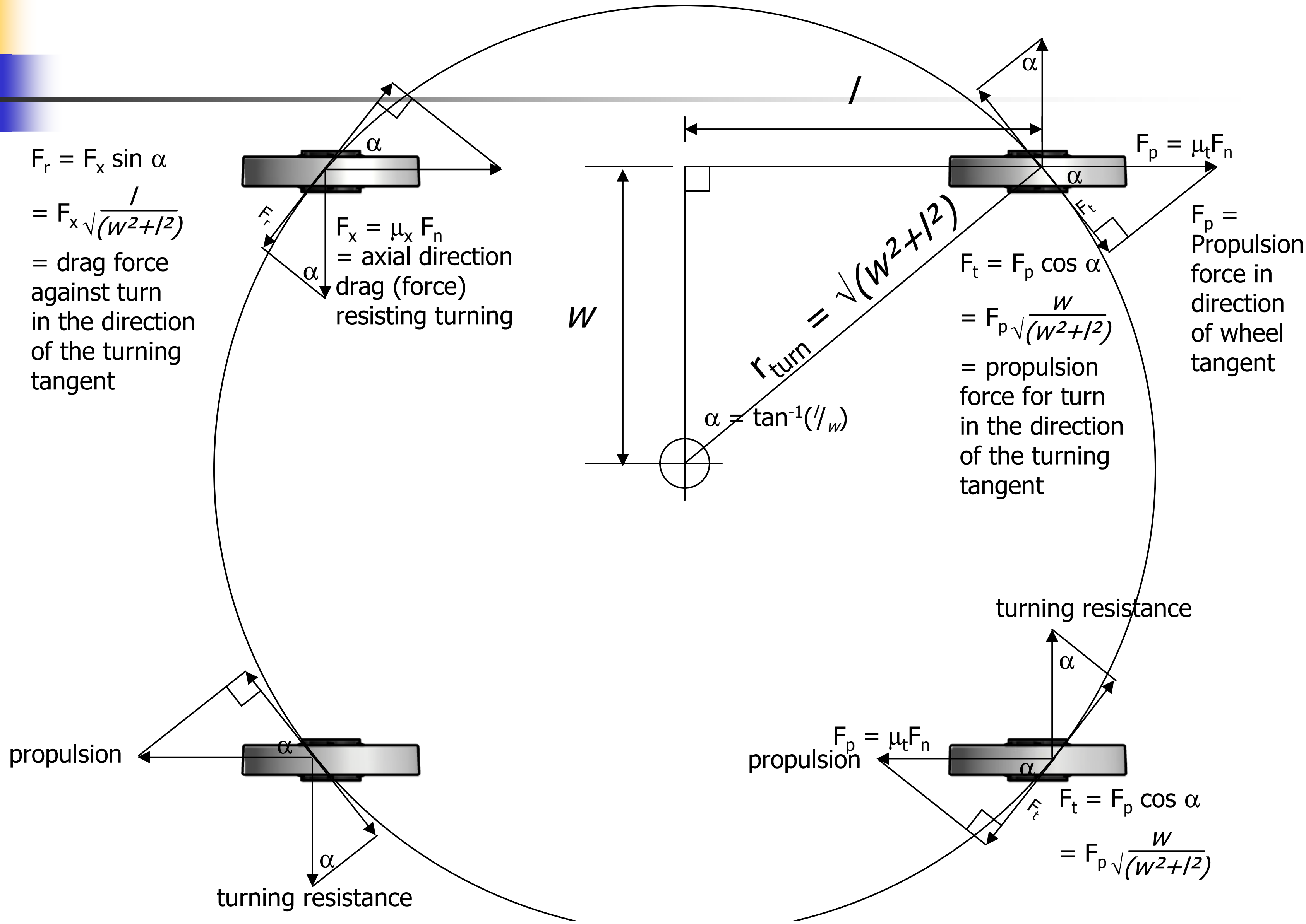

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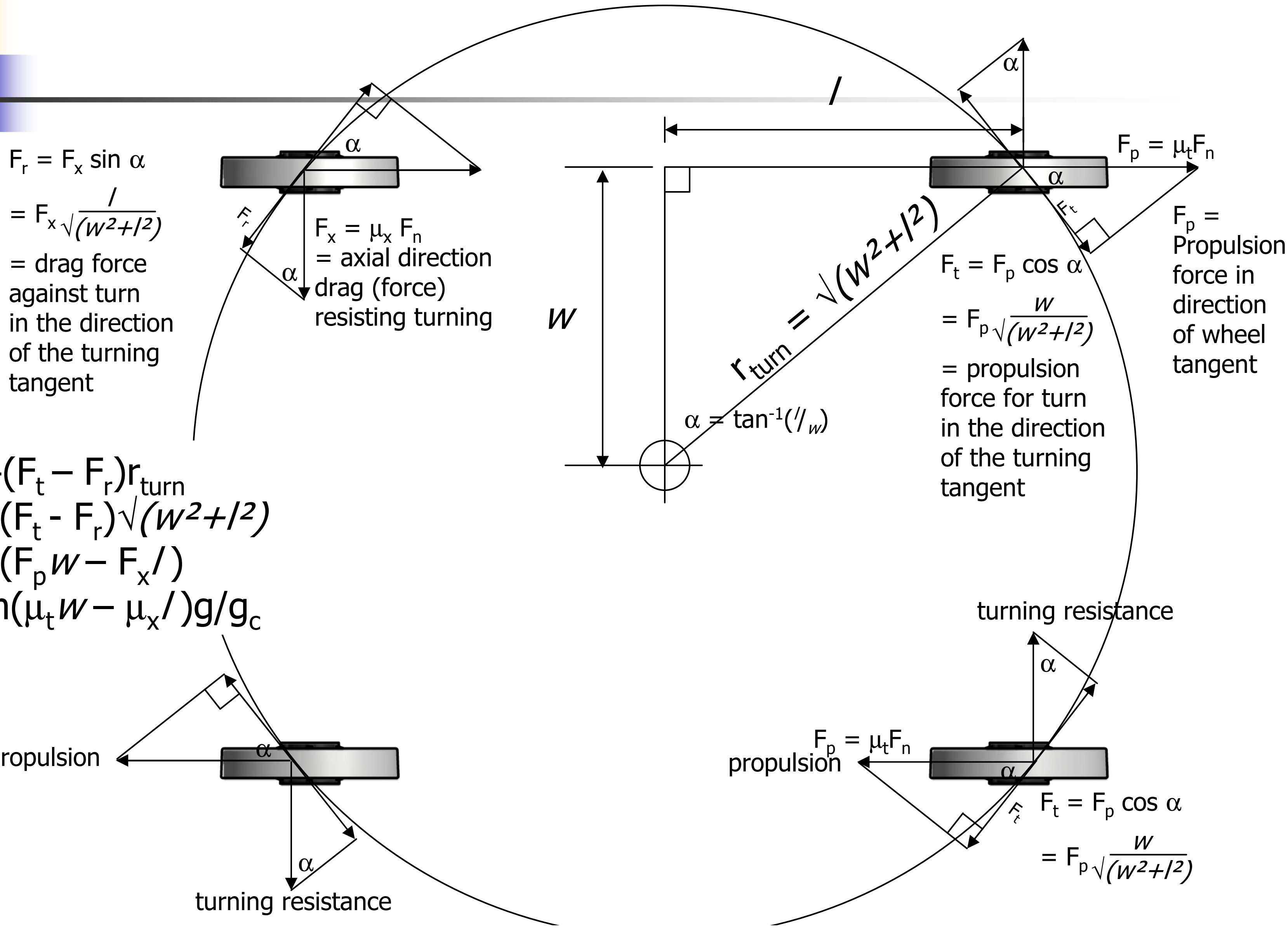
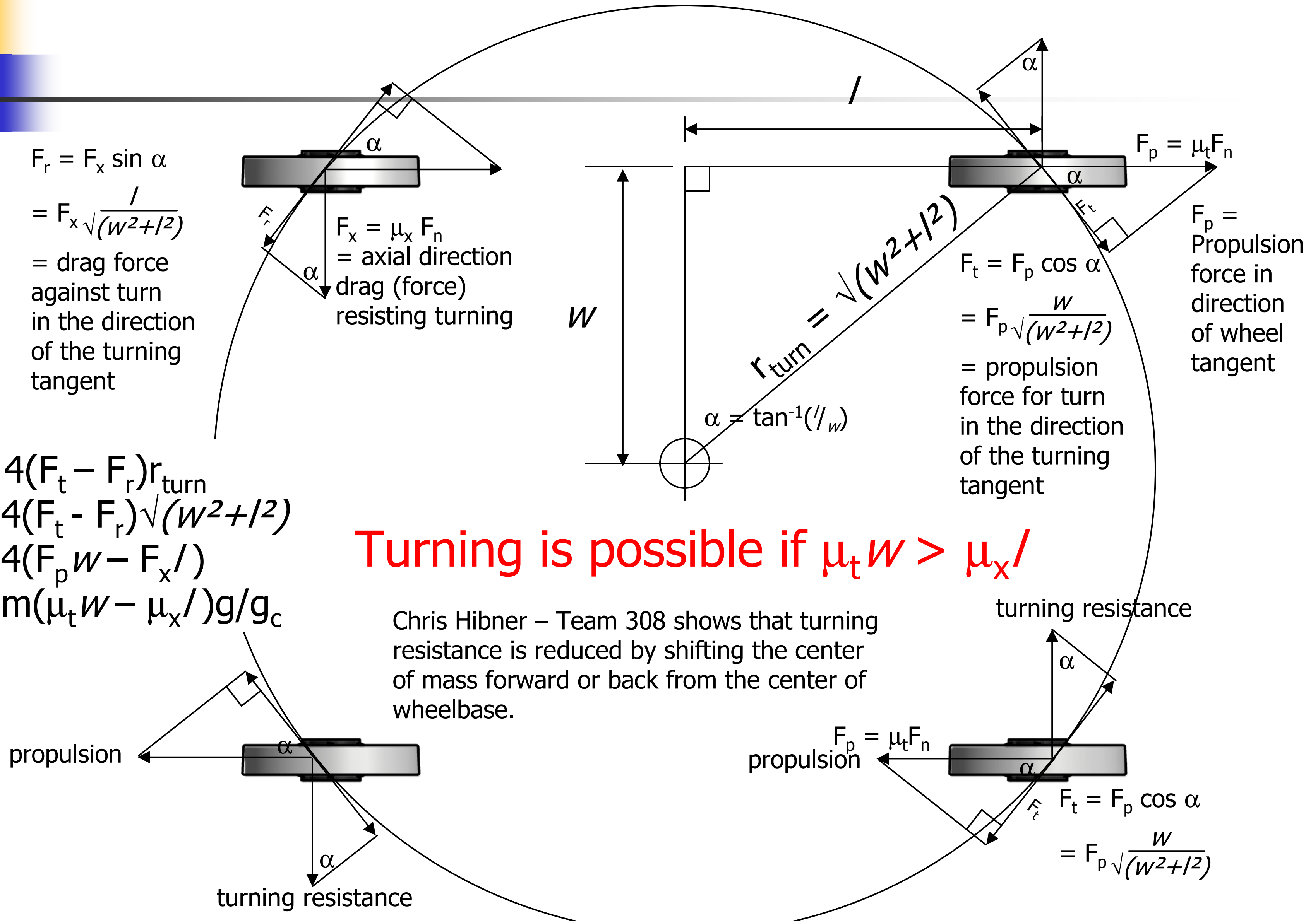


$$
\begin{aligned}
\tau_{turn} &= 4(F_t - F_r)r_{turn} \\
&= 4(F_t - F_r)\sqrt{(w^2+l^2)} \\
&= 4(F_p w - F_x l) \\
&= m(\mu_t w - \mu_x l)g/g_c
\end{aligned}
$$

Stationary turning – 4wd



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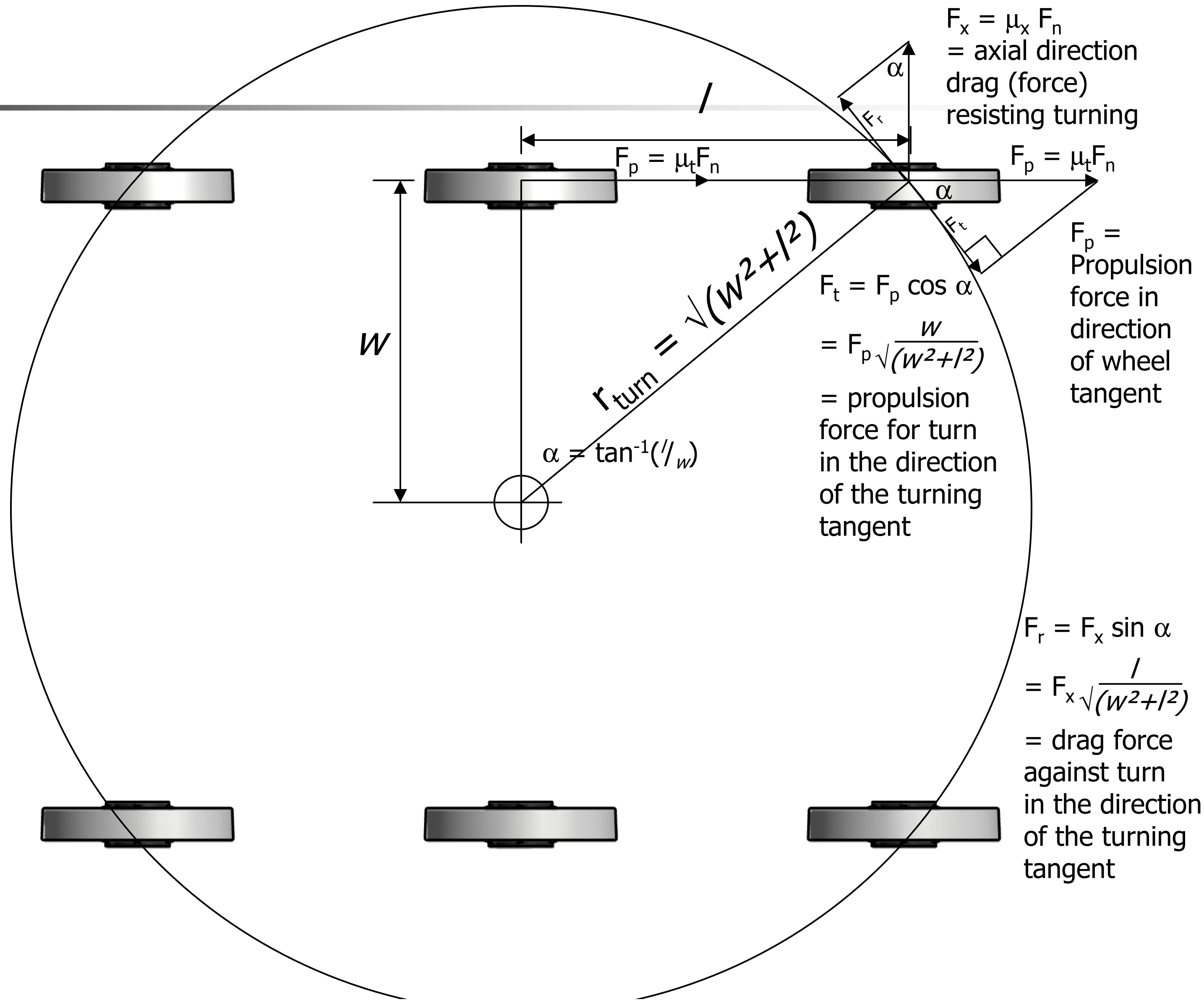
Turning is possible if $\mu_t w > \mu_x l$

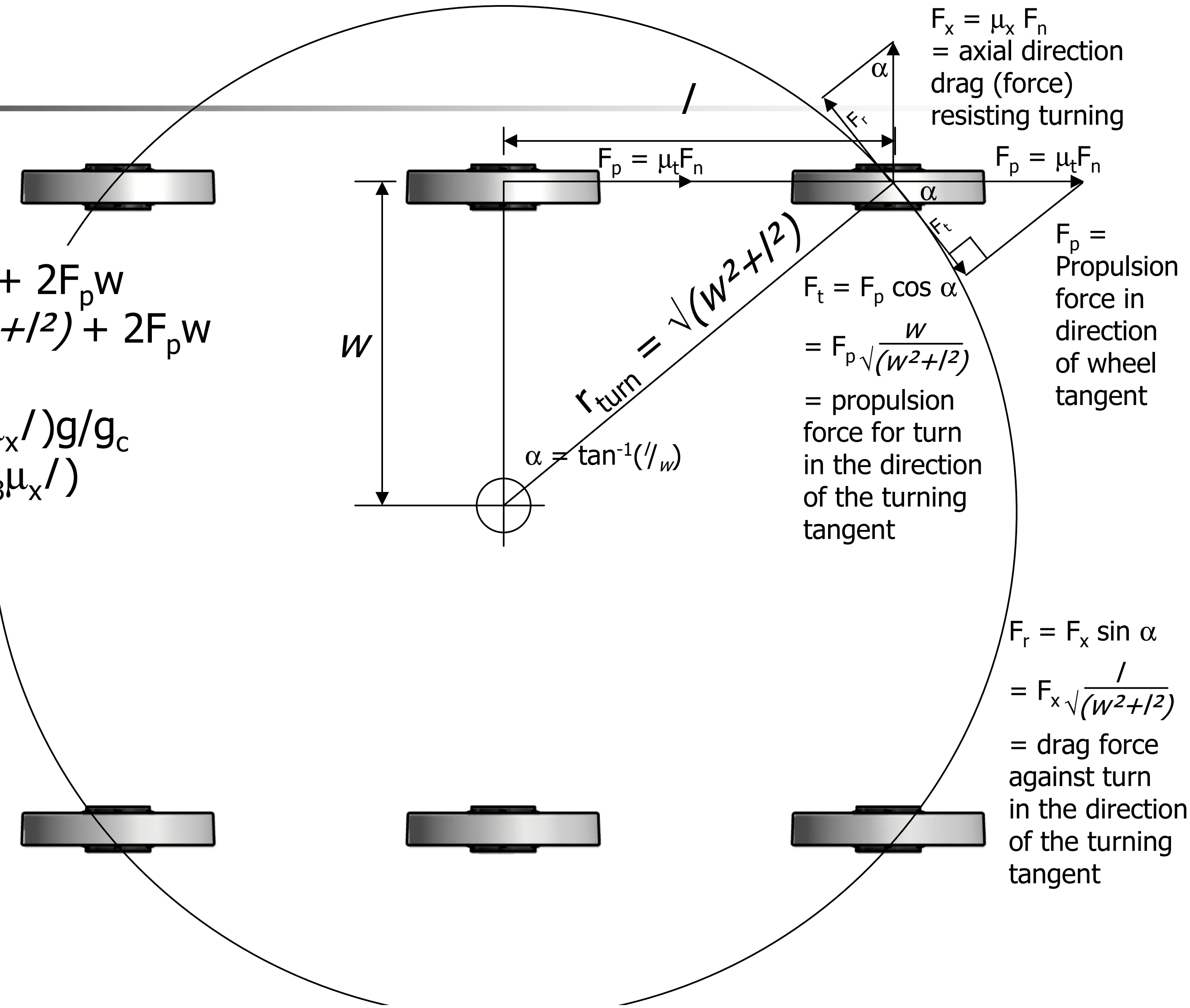
Chris Hibner – Team 308 shows that turning resistance is reduced by shifting the center of mass forward or back from the center of wheelbase.

Stationary turning – 6wd



Stationary turning – 6wd

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



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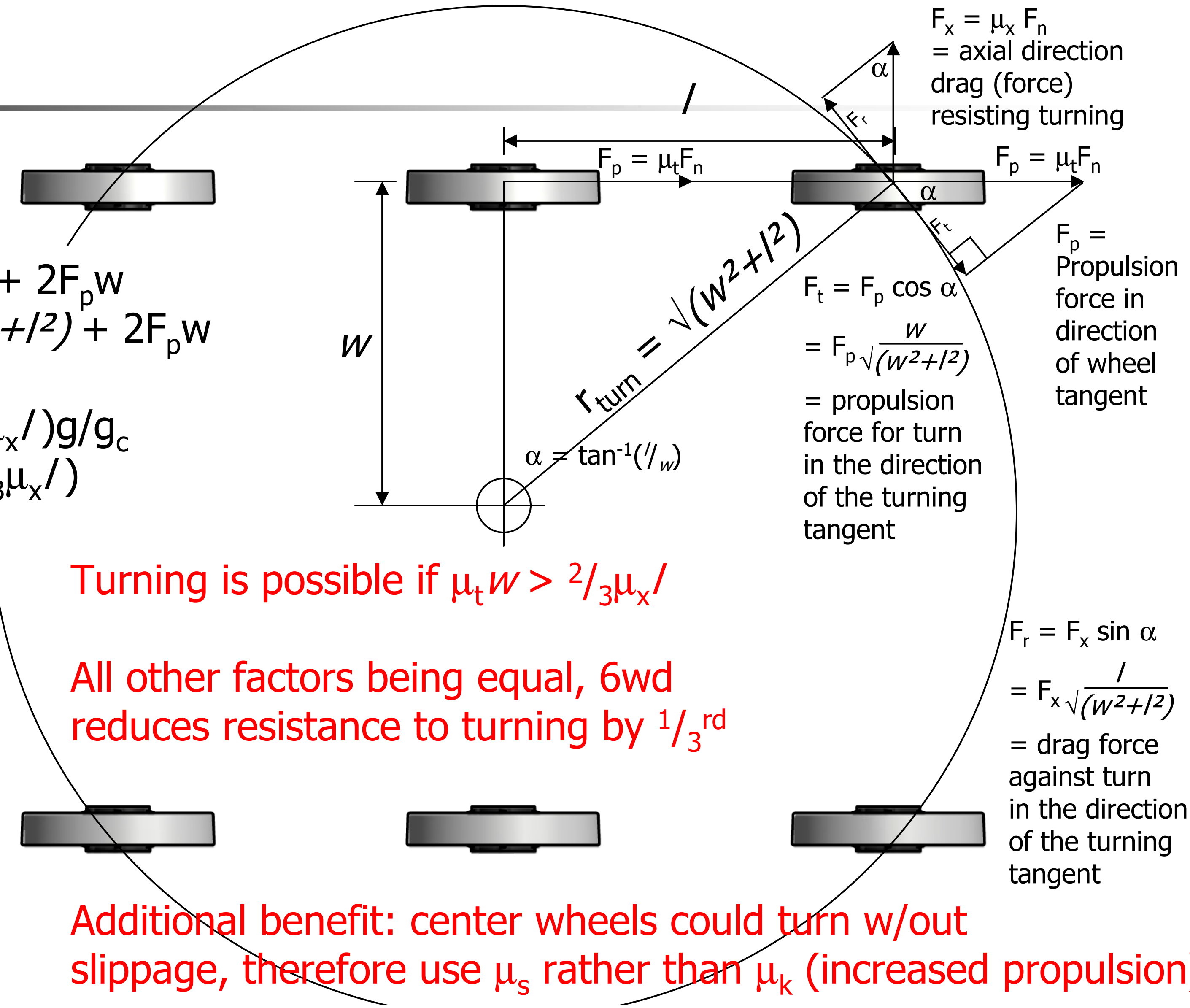

Turning is possible if $\mu_t w > {}^2/_3\mu_x l$

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)

Stationary turning – 6wd

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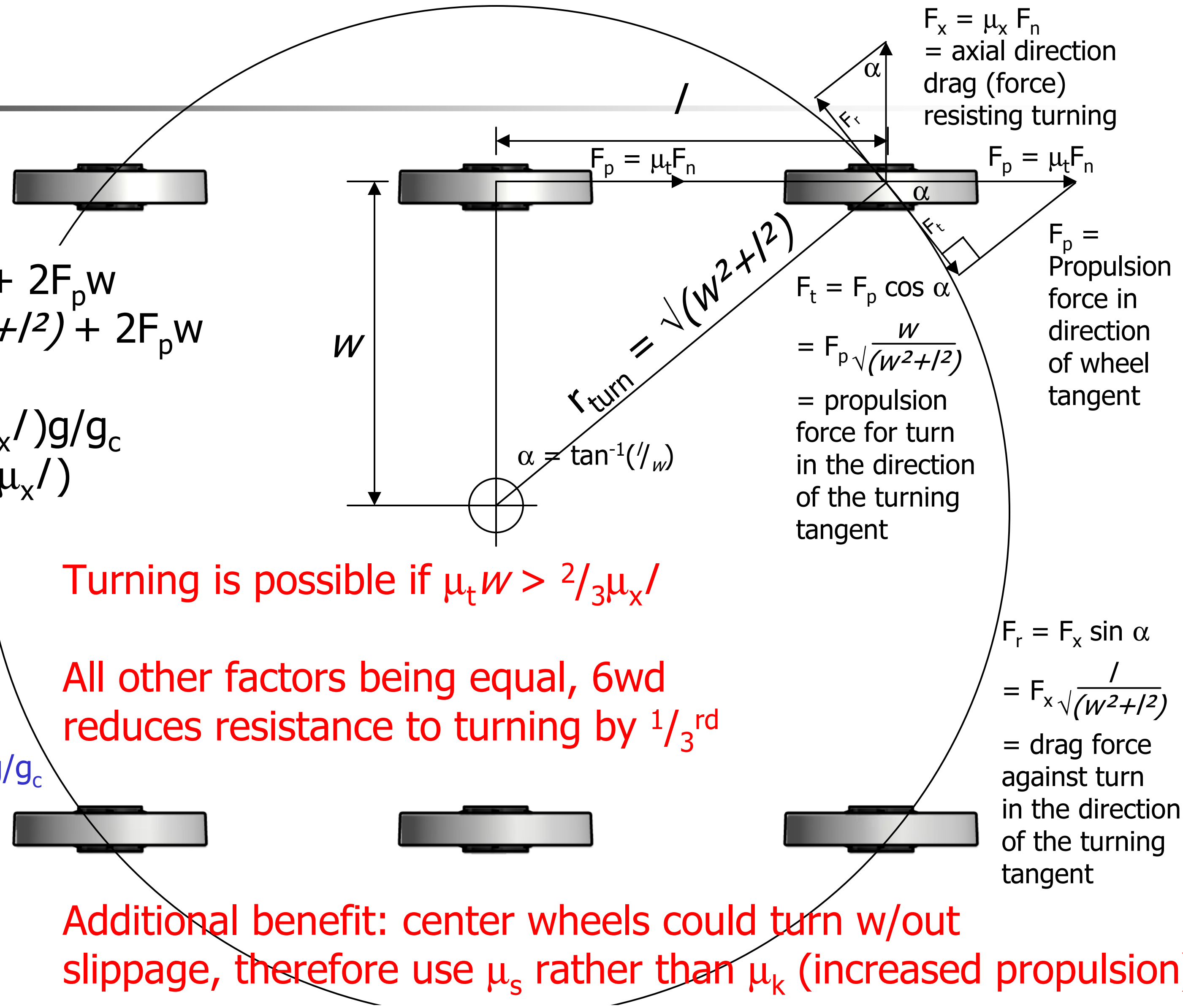

But this is based on Equal weight distribution
Analysis indicates center wheels support disproportionate weight: 40-60% of total - @ 40%:

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

∴ turning benefit of 6wd is considerable

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4wd – 6wd Tank Drive Comparison

4wd Tank Drive *6wd Tank Drive*

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

+ Simplicity

6wd Tank Drive

- More complex

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

+ Simplicity
+ Weight

6wd Tank Drive

- More complex
- Weight (2 wheels)

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

+ Simplicity
+ Weight

6wd Tank Drive

- More complex
- Weight (2 wheels)
- Constrains design

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

\+ Simplicity

\+ Weight

o Traction

6wd Tank Drive

\- More complex

\- Weight (2 wheels)

\- Constrains design

o Traction

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

\+ Simplicity
\+ Weight

o Traction
o Stability

6wd Tank Drive

\- More complex
\- Weight (2 wheels)
\- Constrains design

o Traction
o Stability

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

+ Simplicity
+ Weight

o Traction
o Stability
- Turning

6wd Tank Drive

- More complex
- Weight (2 wheels)
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o Traction
o Stability
+ Turning

4wd – 6wd Tank Drive Comparison

4wd Tank Drive

+ Simplicity
+ Weight

o Traction
o Stability
- Turning
- Steering hysterisis

6wd Tank Drive

- More complex
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o Traction
o Stability
+ Turning
+ Less hysterisis

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

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

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- For traction: Maximize weight & friction coefficients

Conclusions & Good Practices

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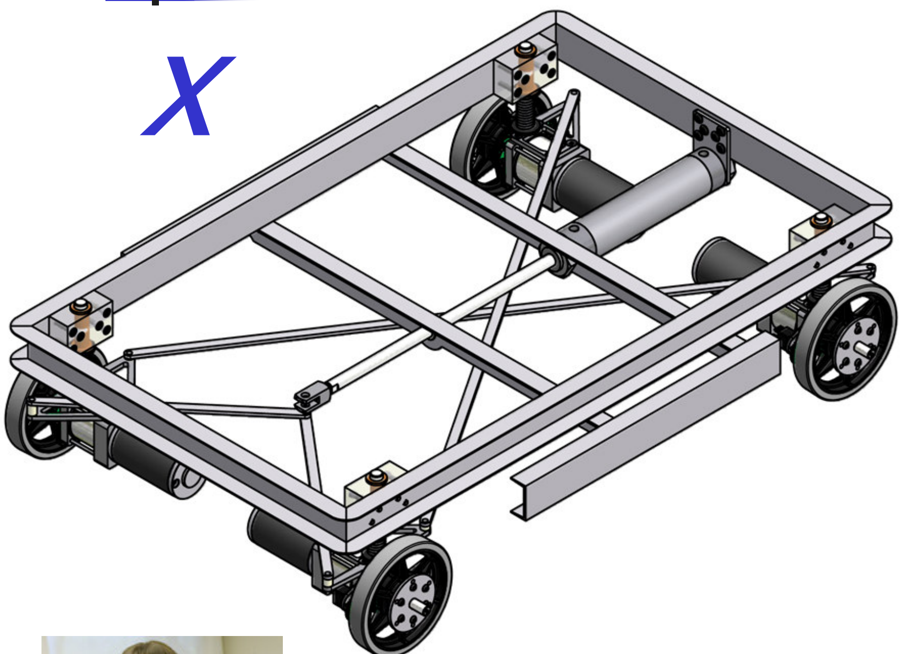
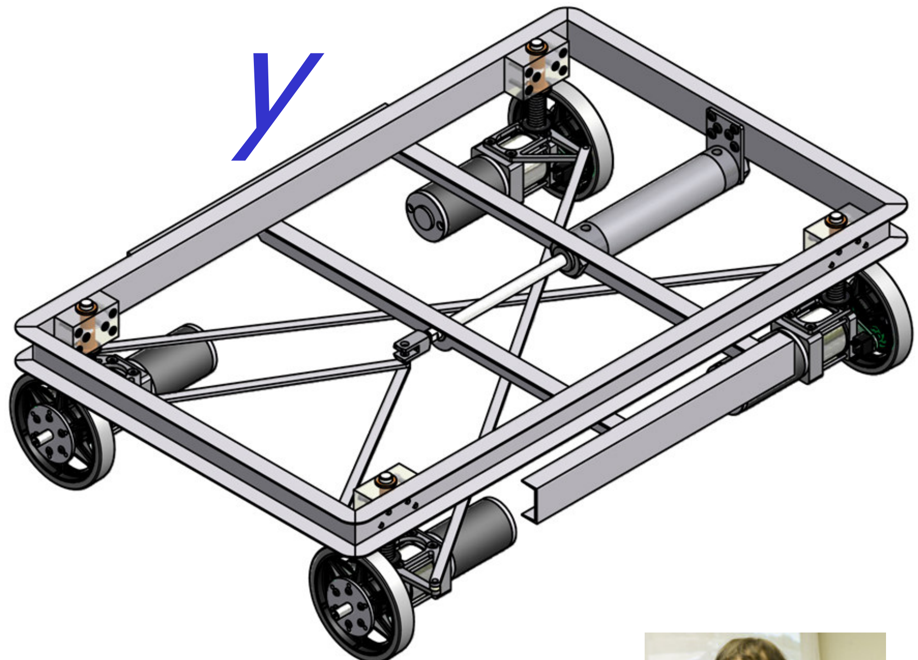
- Omni wheels can improve tank steering – but increase vulnerability to sideways pushing.
- For a robot with a rectangular envelope, given wheelbase, mass and center of gravity, (4) wheels (driven or not) provide the maximum stability. Additional wheels neither help nor hurt.
- A common side drive-train (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

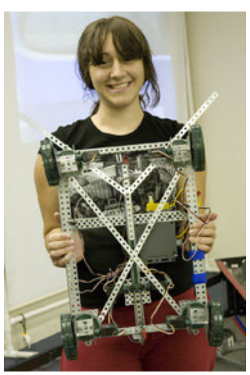
Unconventional Drivetrains

Food for thought

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

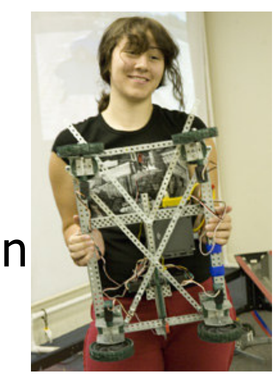




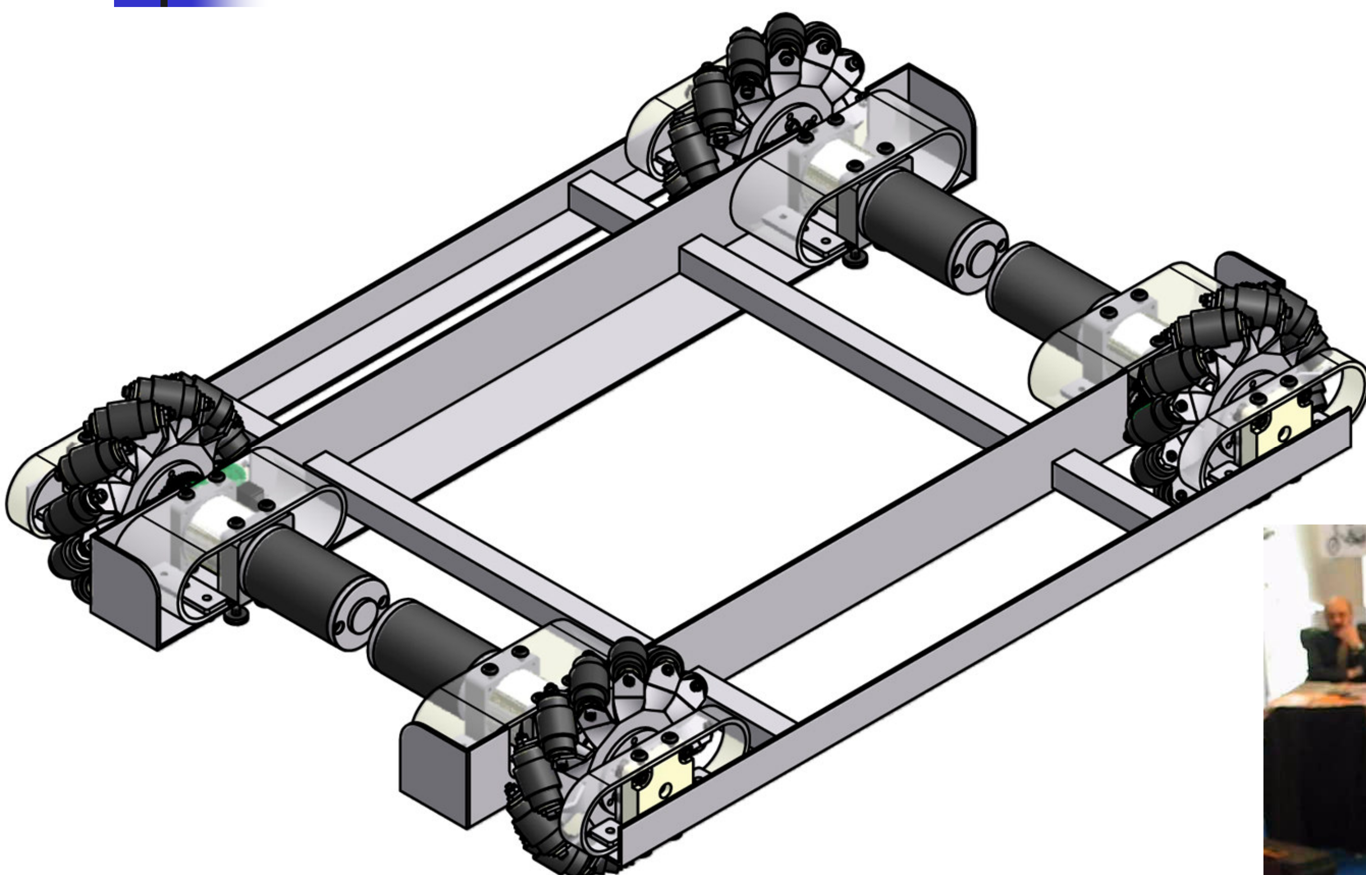


- 2-axis drive (not 2d)
- Fast (pneumatic) switch
- Agile
- Steers well in y-mode
- Poor steering x-mode

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

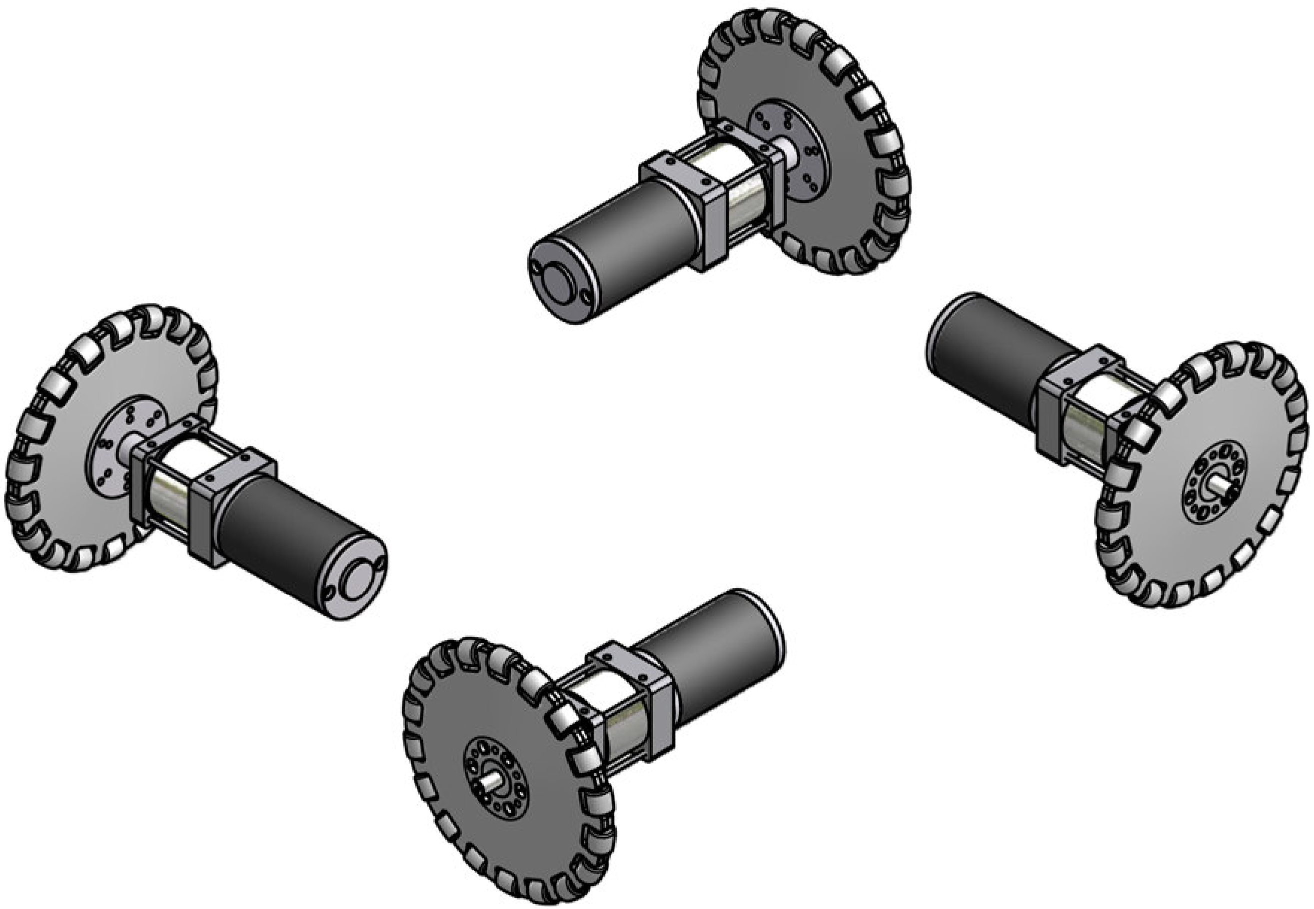


Mecanum Drive
true 2-d maneuverability



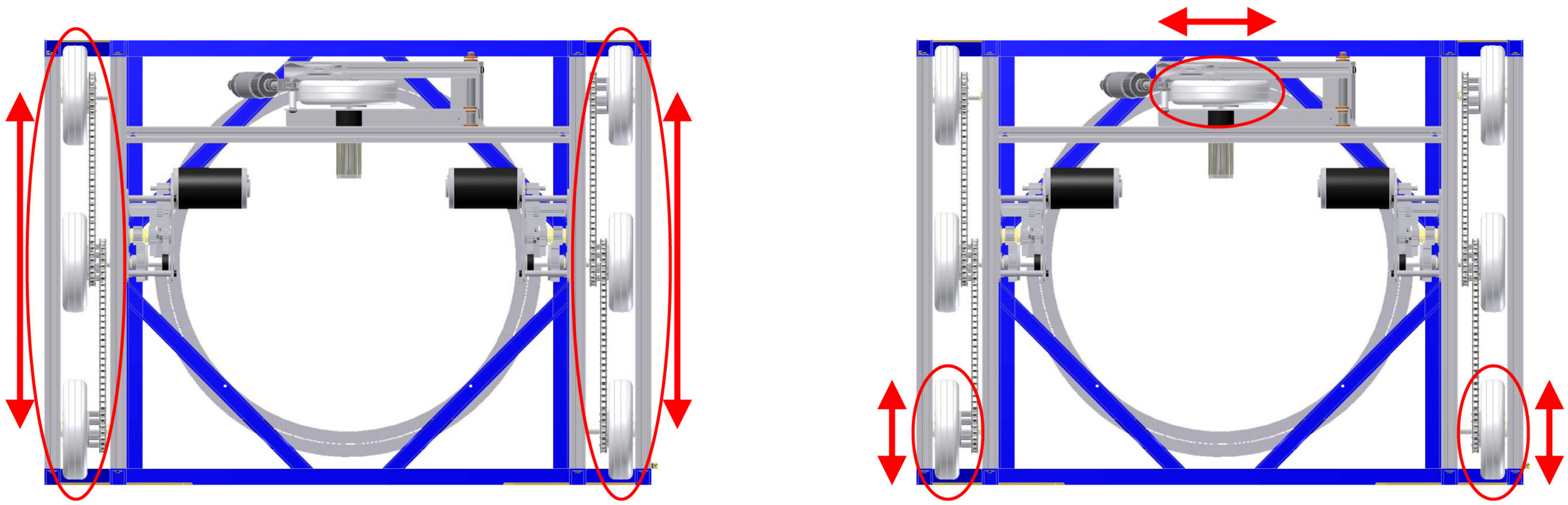
- 2-d drive
- Compatable w/ suspension
- Very cool
- Moderately popular
- 1640 has no experience

"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	+	+	++	-	-	