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
Motors convert electrical power (W) to rotational power (W)

Power output is controlled via Pulse Width Modulation of the input 12 V DC

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

\[ F_d = \text{Drive Force} \]
\[ F_d = \frac{\tau}{r} \]

\[ \mu = \text{coefficient of friction} \]

For objects not sliding relative to each other
\[ \mu = \mu_s \text{ (static coefficient of friction)} \]

For objects sliding relative to each other
\[ \mu = \mu_k \text{ (kinetic coefficient of friction)} \]

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

\[ F_f = \text{Friction Force} \]
\[ F_f = \mu F_n \]

\[ F_n = \text{normal force between frictive surfaces} \]

For a 120 lbm robot with weight equally distributed over four wheels, \( F_n \) would be 30 lb at each wheel.

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

\[ \tau = \text{torque} \]
\[ r = \text{wheel radius} \]

\[ F_p = \text{Propulsive Force} \]

\[ F_p = -F_d; \quad F_p \leq F_{fs} \]

For wheels not sliding on drive surface:
\[ \mu_s \]

For wheels slipping on drive surface:
\[ \mu_k \]

\[ F_f = \mu F_n \]

\[ F_f = \mu_s F_n \text{ (static friction)} \]
\[ F_f = \mu_k F_n \text{ (kinetic friction)} \]

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

\[
\frac{dv}{dt} = \frac{G \tau_{MS} g_c}{mr_w} \left(1 - \frac{\tau_{ML}}{\tau_{MS}} - \frac{G}{2\pi r_w v_{MU}}\right)
\]
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

Motor

Transmission

Reduces rpm while increasing torque to useful levels

Differential

Provides equal drive torque to Left & Right drive wheels

Suspension

Maintains wheel contact on uneven surface

Suspension

Motor

Power source

Differential provides equal drive torque to Left & Right drive wheels.

Transmission reduces rpm while increasing torque to useful levels.

Steering

Front wheels change angle to direct line of travel.
How a (typical) robot drives

Motor

Power source

Transmission

Reduces rpm while increasing torque to useful levels

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

<table>
<thead>
<tr>
<th><strong>Automobile Drive</strong></th>
<th><strong>Robot (Tank) Drive</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficient steering</td>
<td>High energy steering</td>
</tr>
<tr>
<td>Smooth steering</td>
<td>Steering hysterisis</td>
</tr>
<tr>
<td>Avoids wheel sliding</td>
<td>Wheels slide to turn</td>
</tr>
<tr>
<td>Low wheel wear</td>
<td>High wheel wear</td>
</tr>
<tr>
<td>Large turn radius</td>
<td>Zero turning radius</td>
</tr>
<tr>
<td>Cannot turn in place</td>
<td>Turns in place</td>
</tr>
<tr>
<td>Limited traction</td>
<td>Improved traction</td>
</tr>
</tbody>
</table>
4wd – 6wd Comparison
Propulsion Force \( (F_p) \) – Symmetric 4wd

**Assumptions / Variables:**
- \( \tau \): torque available at each axle
- \( m \): mass of robot
- \( F_n \): Normal force per wheel
  - \( = \frac{1}{4} \) m g/g_c (SI: \( F_n = \frac{1}{4} \) m g)
  - evenly weighted wheels
- \( r_w \): wheel radius

**Rolling without slipping:**
\[
F_{p/w} = \frac{\tau}{r_w} \quad \text{up to a maximum of} \quad F_{p/w} = \mu_s F_n
\]

**Pushing with slipping:**
\[
F_{p/w} = \mu_k F_n
\]

**Robot Propulsion Force**
\[
F_{p/R} = \sum F_{p/w}
\]

**Rolling without slipping:**
\[
F_{p/R} = 4\frac{\tau}{r_w}
\]

**Pushing with slipping:**
\[
F_{p/R} = 4\mu_k F_n = \mu_k m g/g_c \quad \text{(SI:)}
F_{p/R} = \mu_k m g
\]

Does not depend on evenly weighted wheels
**F_p - Symmetric 6wd**

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

Propulsion Force per wheel

Rolling without slipping:
$$F_{p/w} = \frac{2}{3}\frac{\tau}{r_w}$$
- up to a maximum of $F_{p/w} = \mu_s F_n$

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

Robot Propulsion Force
$$F_{p/R} = \sum F_{p/w}$$

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

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:
  - $\mu_t$ – wheel/floor coefficient of friction in wheel tangent direction
  - $\mu_x$ – wheel/floor coefficient of friction in wheel axial direction (omni-wheels provide $\mu_x \ll \mu_t$)
  - $F_x$ – wheel drag force in wheel axis direction
Stationary turning – 4wd

\[ F_r = F_x \sin \alpha \]
\[ = F_x \sqrt{w^2 + l^2} \]

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

\[ F_x = \mu_x F_n \]

= axial direction drag (force) resisting turning

\[ F_t = F_p \cos \alpha \]

= propulsion force for turn in the direction of the turning tangent

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

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

\[ \tau_{\text{turn}} = 4(F_t - F_r)r_{\text{turn}} + 2F_p w \]
\[ = 4(F_t - F_r)\sqrt{w^2 + l^2} + 2F_p w \]
\[ = 6F_p w - 4F_x / \]
\[ = m(\mu_t w - 2/3\mu_x /)g/g_c \]

(SI) \[ = mg(\mu_t w - 2/3\mu_x /) \]

\[ F_x = \mu_x F_n \]

= axial direction drag (force) resisting turning

\[ F_p = \mu_t F_n \]

= propulsion force in the direction of wheel tangent

\[ F_r = F_x \sin \alpha \]

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

Turning is possible if \( \mu_t w > 2/3\mu_x / \)

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 \( \mu_s \) rather than \( \mu_k \) (increased propulsion)
4wd – 6wd Tank Drive Comparison

**4wd Tank Drive**
+ Simplicity
+ Weight
  - Traction
  - Stability
- Turning
- Steering hysterisis
- Wheel wear

**6wd Tank Drive**
- More complex
- Weight (2 wheels)
- Constrains design
  - Traction
  - Stability
+ Turning
+ Less hysterisis
+ 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

- 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
- Compatible 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
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

<table>
<thead>
<tr>
<th>Drive Type</th>
<th>Steering Ease</th>
<th>Turn Radius</th>
<th>Agility</th>
<th>Traction</th>
<th>Ramp Climbing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>++</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4wd Tank</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>6wd Tank</td>
<td>+</td>
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<td>0</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Twitch</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
</tr>
<tr>
<td>Mecanum</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Daisy</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

} Speculative
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

Driving a circle in Snake mode