Robot Drive System Fundamentals

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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

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

- \( F_{\text{friction}} = \mu \times F_{\text{normal}} \)
- Experimentally determine \( \mu \):
- \( F_{\text{normal}} = \text{Weight} \times \cos(\theta) \)
- \( F_{\text{parallel}} = \text{Weight} \times \sin(\theta) \)

When \( F_{\text{friction}} = F_{\text{parallel}} \), no slip

\[
\begin{align*}
F_{\text{friction}} &= \mu \times \text{Weight} \times \cos(\theta) \\
F_{\text{parallel}} &= \text{Weight} \times \sin(\theta) = \mu \times \text{Weight} \times \cos(\theta)
\end{align*}
\]

\( \mu = \frac{\sin(\theta)}{\cos(\theta)} \quad \mu = \tan(\theta) \)
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

<table>
<thead>
<tr>
<th>High Friction Coeff:</th>
</tr>
</thead>
<tbody>
<tr>
<td>soft materials</td>
</tr>
<tr>
<td>“spongy” materials</td>
</tr>
<tr>
<td>“sticky” materials</td>
</tr>
</tbody>
</table>

| 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.
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

arm position in rear makes the weight shift to the rear

arm position in front makes the weight shift to the front

EXAMPLE ONLY

normal force (rear)

normal force (front)
"Enhanced" Traction
Traction Fundamentals
“Weight Transfer”

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

Drive elements can:
- steer (to enable turning or “crabbing”)
- move up and down (to engage/disengage, or to enable climbing)

** Can combine some of these features together **

Advice: Don’t make it more complex than it has to be!
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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 ($\omega_f$)
  - Free Current ($A_f$)
Slope-Intercept \((Y=mX + b)\)

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

What is \(K\) … It is the slope of the line.

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

\(K = \text{Slope} = -T_0/\omega_f\)
(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:

\[ \text{Torque} = (-T_0/\omega_f) \times \text{Speed} + T_0 \]
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

- $T_{40} = \text{Torque at 40 Amps}$
- $\omega_{40} = \text{Speed at 40 Amps}$

Current Equation:
Current = $(A_f - A_0)/\omega_f \times \text{Speed} + A_0$

Motor Equation:
Torque = $(-T_0/\omega_f) \times \text{Speed} + T_0$
Power - Max vs. 40 Amps

Power = Torque * Speed

Must give up torque for speed

Max Power occurs when:

\[ T = \frac{T_0}{2} \quad \text{and} \quad \omega = \frac{\omega_f}{2} \]

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 $T_0$, $\omega_f$, $A_0$, $A_f$, $T_{40}$, $\omega_{40}$, max power ($P_{max}$), amps @ max power ($A_{pmax}$), and power at 40 amps ($P_{40}$).
## Motor Comparisons

<table>
<thead>
<tr>
<th>Motor</th>
<th>$T_0$</th>
<th>$W_f$</th>
<th>$A_0$</th>
<th>$A_f$</th>
<th>$P_{max}$</th>
<th>$T_{40}$</th>
<th>$W_{40}$</th>
<th>$P_{40}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N-m</td>
<td>RPM</td>
<td>Amps</td>
<td>Amps</td>
<td>Watts</td>
<td>N-m</td>
<td>RPM</td>
<td>Watts</td>
</tr>
<tr>
<td>CIM</td>
<td>2.45</td>
<td>5,342</td>
<td>114</td>
<td>2.4</td>
<td>342.6</td>
<td>0.80</td>
<td>3,647</td>
<td>305.5</td>
</tr>
<tr>
<td>Mabuchi F.P.</td>
<td>0.642</td>
<td>24,000</td>
<td>148</td>
<td>1.5</td>
<td>403.4</td>
<td>0.18</td>
<td>17,500</td>
<td>322.5</td>
</tr>
</tbody>
</table>

Motor Equations:

1. 2006 Fisher-Price: \[ T = \left(-\frac{0.64}{24,000}\right) \cdot \omega + 0.64 \]
2. 2002-07 Chiaphua: \[ T = \left(-\frac{2.45}{5,342}\right) \cdot \omega + 2.45 \]
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!!

$$\omega_f \text{ FP} / \omega_f \text{ Chiaphua} = 24,000/5342 \sim 9/2 = \text{Gear Ratio}$$

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

More to come on Gear Ratio & Efficiency a little later!
### Combined Motor Data

<table>
<thead>
<tr>
<th>Motor</th>
<th>T0</th>
<th>Wf</th>
<th>Pmax</th>
<th>T40</th>
<th>W40</th>
<th>P40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N·m</td>
<td>RPM</td>
<td>Watts</td>
<td>N·m</td>
<td>RPM</td>
<td>Watts</td>
</tr>
<tr>
<td>F-P &amp; CIM</td>
<td>5.19</td>
<td>5,337</td>
<td>725</td>
<td>1.7</td>
<td>3,642</td>
<td>648</td>
</tr>
<tr>
<td>CIM &amp; CIM</td>
<td>4.9</td>
<td>5,342</td>
<td>685</td>
<td>1.6</td>
<td>3,647</td>
<td>611</td>
</tr>
<tr>
<td>CIM, CIM, &amp; F-P</td>
<td>7.64</td>
<td>5,339</td>
<td>1068</td>
<td>2.63</td>
<td>3,644</td>
<td>1004</td>
</tr>
</tbody>
</table>

**Motor Equations:**

1. **F-P & CIM:** \( T = \left(-\frac{5.19}{5,337}\right) \omega + 5.19 \)
2. **CIM & CIM:** \( T = \left(-\frac{4.9}{5,342}\right) \omega + 4.9 \)
3. **CIM, CIM, & F-P:** \( T = \left(-\frac{7.64}{5,339}\right) \omega + 7.64 \)
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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%
   \( GR = \frac{N_2}{N_1} \)

2. Spur Gears
   Efficiency ~ 95% - 98%
   \( GR = \frac{N_2}{N_1} \)
Types of Drive Mechanisms

3. Bevel Gears

Efficiency ~ 90% - 95%

\[ GR = \frac{N_2}{N_1} \]
Types of Drive Mechanisms

4. Worm Gears
   Efficiency ~ 40% - 70%
   \# Teeth on Worm Gear
   \[ GR = \frac{\text{\# Teeth on Worm Gear}}{\text{\# of Threads on worm}} \]
Types of Drive Mechanisms

5. Planetary Gears
   Efficiency ~ 80% - 90%

\[
GR = \frac{N_{\text{ring}}}{N_{\text{sun}}} + 1
\]
Gearing Basics

• Consecutive gear stages multiply:

\[ \frac{N_2}{N_1} \times \frac{N_4}{N_3} \]

• Gear Ratio is \( \frac{N_2}{N_1} \times \frac{N_4}{N_3} \)

• Efficiency is \( .95 \times .95 = .90 \)
Gearing Basics - Wheel Attachment

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

Motor Shaft

Wheel Diameter - $D_w$

$D_w = R_w \times 2$

Wheel Attachment - $N_1$, $N_2$, $N_3$, $N_4$
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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 ???

\[ F_{\text{max}} = F_{\text{friction}} = \mu \times (W + W_t) \quad \{\text{on a flat surface}\} \]

Now \( T = F \times R_w \quad \longrightarrow \quad F = \frac{T_{out}}{R_w} \)
Design Condition Continued

\[ T_{out} = T_{40} \times \text{GR} \times \text{eff} \]

\[ F_{\text{friction}} = \frac{T_{out}}{R_w} : \mu \times (W + W_t) = \frac{T_{40} \times \text{GR} \times \text{eff}}{R_w} \]

\[ \frac{\mu \times (W + W_t)}{GR/R_w} = \frac{GR/R_w}{T_{40} \times \text{eff}} \]

The above gives you the best combination of gear ratio and wheel diameter for maximum pushing force!
O.K. So what is my top speed?

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

Where \( \omega_{\text{free}} \) 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
- $\mu = 0.8$
- $\text{eff} = 0.86$
- $T_{40} = 2 \times 1.18$ ft-lb
- $R_w = 4$ in

\[
GR/R_w = \frac{0.8 \times (130 + 0)}{2 \times 1.18 \times 0.86}
\]

$GR = 17$

Actual kit gear ratio is

\[
50/14 \times 50/14 \times 28/21 = 17
\]
Design Condition Applied to Kit Transmission Design

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

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

\[
F_{\text{max}} \text{ [lb]} = \frac{2 \times 1.18 \times 17 \times 0.86}{4/12} = 103.5 \text{ lb}
\]

\[
F_{\text{max \ available}} = 0.8 \times (130 + 0) = 104 \text{ lb}
\]
# Gearing Fundamentals

## Robot Drive System Simulation

### Gear Ratio Input Data

<table>
<thead>
<tr>
<th>Gearbox Ratio (drill motor speed : output speed)</th>
<th>60</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive Sprocket # of Teeth</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Driven Sprocket # of Teeth</td>
<td>39</td>
<td>41</td>
</tr>
</tbody>
</table>

### Gearbox Constants

- 0.908: Gearbox efficiency (not rest of driveline)
- 0.93: Gearbox input side efficiency (Nm)

### Robot Input Data

- **Efficiency Constants**
  - 0.1016: Drive wheel radius (m)
  - 0.000156: Fstatic (N)
  - 0.005: I @motor
  - 58.98367: Mass of robot (kg)
  - 0.95: Ndrive line
  - 0.93: Ntires

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>V (m/s)</th>
<th>V (mph)</th>
<th>Tb, out (Nm)</th>
<th>Tgb, out (Nm)</th>
<th>dv/dt (g)</th>
<th>dv/dt (g/min)</th>
<th>Current (A)</th>
<th>Power (W)</th>
<th>Torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>8.76</td>
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This motor curve is used, based on the inputs in the motors spreadsheet.

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**See John V-Neun's presentation and team 229's website**

Available on the web at [www.huskiebrigade.com](http://www.huskiebrigade.com)
Simulation Results

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
Best New Drive System Component!

chain tensioner
Team 1140 got this from McMaster-Carr

THANK YOU Team 1140!!
Drive System Fundamentals

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