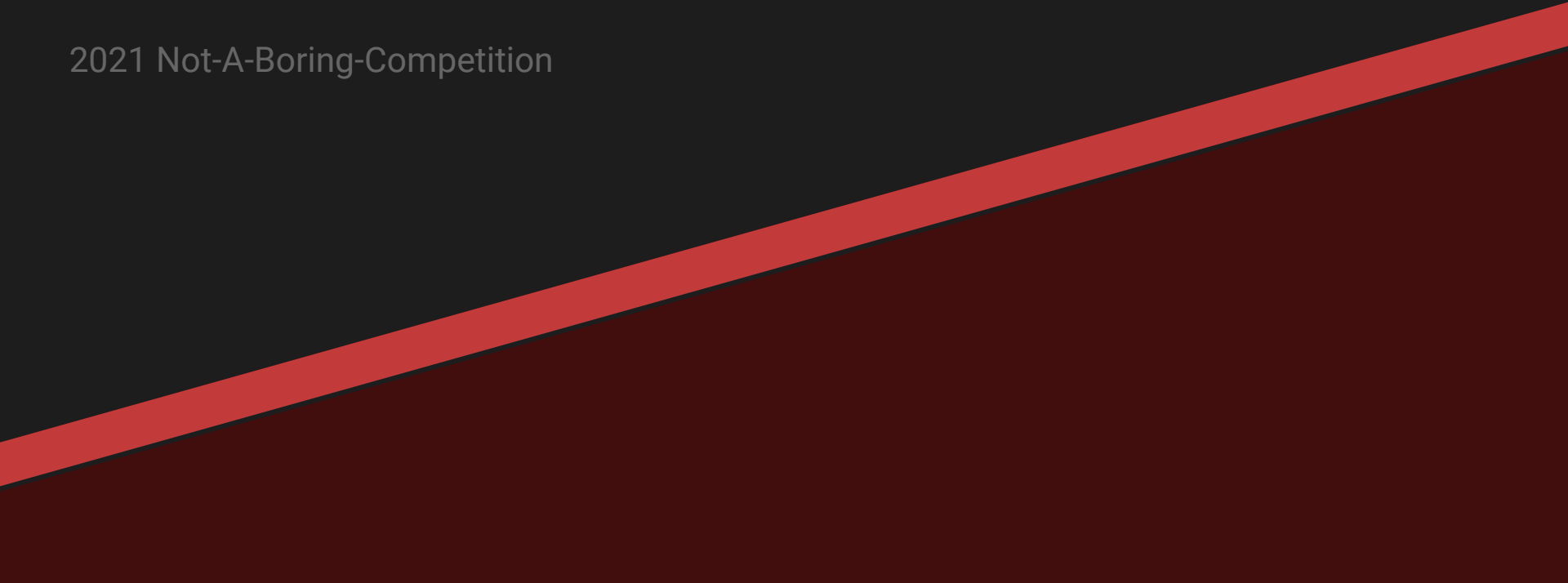


Double Arrow LLC

Preliminary Design Briefing

2021 Not-A-Boring-Competition

A thick, dark red diagonal line runs from the bottom left towards the top right, separating the dark grey upper section from the dark red lower section.

The Team: Double Arrow LLC

Founded to focus on small scale manufacturing and advanced technology development in autonomous systems

Cole Kenny



- B.S. Aerospace Engineering
- Founder of Double Arrow LLC
- 1st year PhD student at the University of Colorado Boulder

Jack Maydan



- M.S. Aerospace Engineering
- Spacecraft Systems Engineer at LASP / NASA JPL

Grant Novota



- B.S. Electrical & Computer Engineering
- Spacecraft Test Engineer at Blue Canyon Technologies



Design Philosophy

In the design approach for this competition, the Double Arrow LLC team intended to use a robust and high margin architecture driven by primarily commercial-off-the-shelf products.

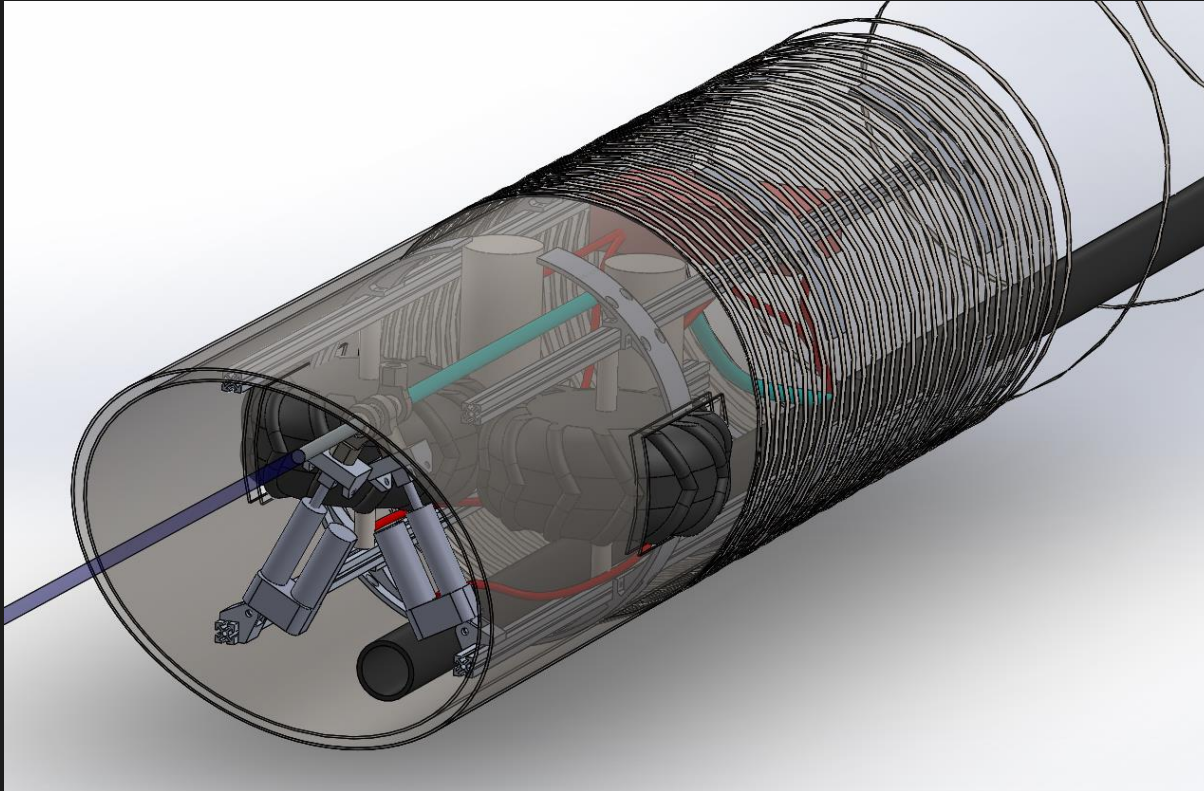
The architecture uses a high pressure water jet to displace and fluid-ify solids in front of the boring machine. The jet is pointed via two gimbals for full coverage of the cutting face and beyond. The fluid and mixed-in solids are vacuumed from the bottom of the cutting face and out of the tunnel.

By using an off the shelf pressure washer and parallelized standard shop vacuums, the Double Arrow LLC team needs only to integrate a semi-modular control system and power regulation system to bore tunnels.

The rough and robust design drives down monetary costs and engineering resource demand, making it a competitive and capable architecture.



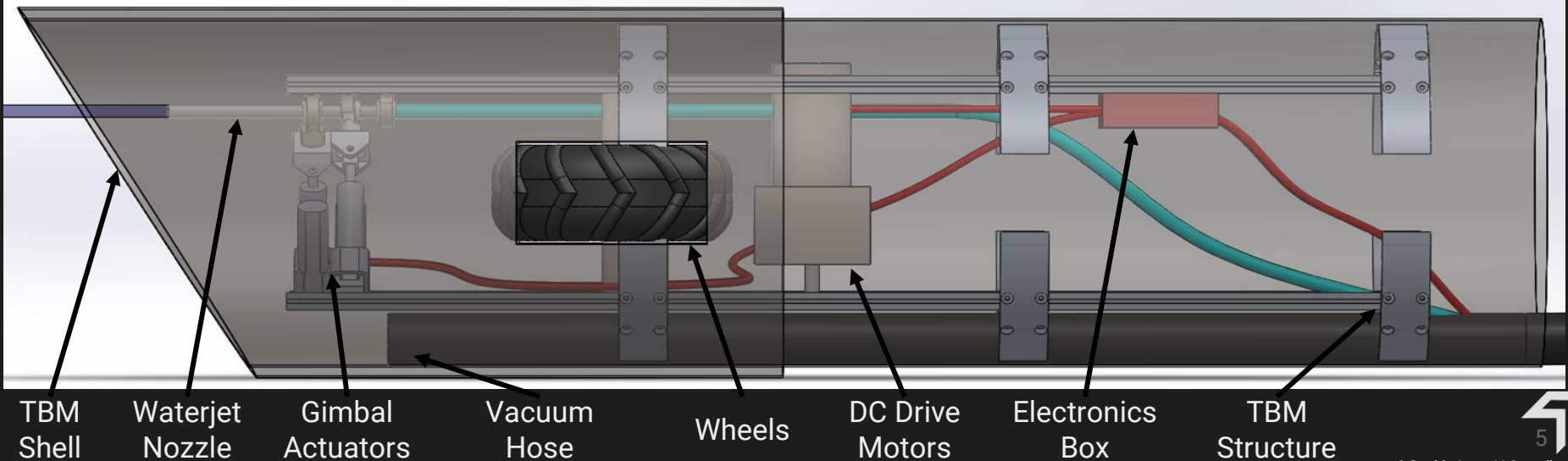
Top Level Overview



Quick Specs Table

Primary Boring Mechanism	Gimbaled Waterjet
Spoils Removal Mechanism	Vacuum
Propulsion Mechanism	Wheels
Support Mechanism	Spiral Tunnel
Estimated Mass	240 lbs 109 kg

Top Level Overview

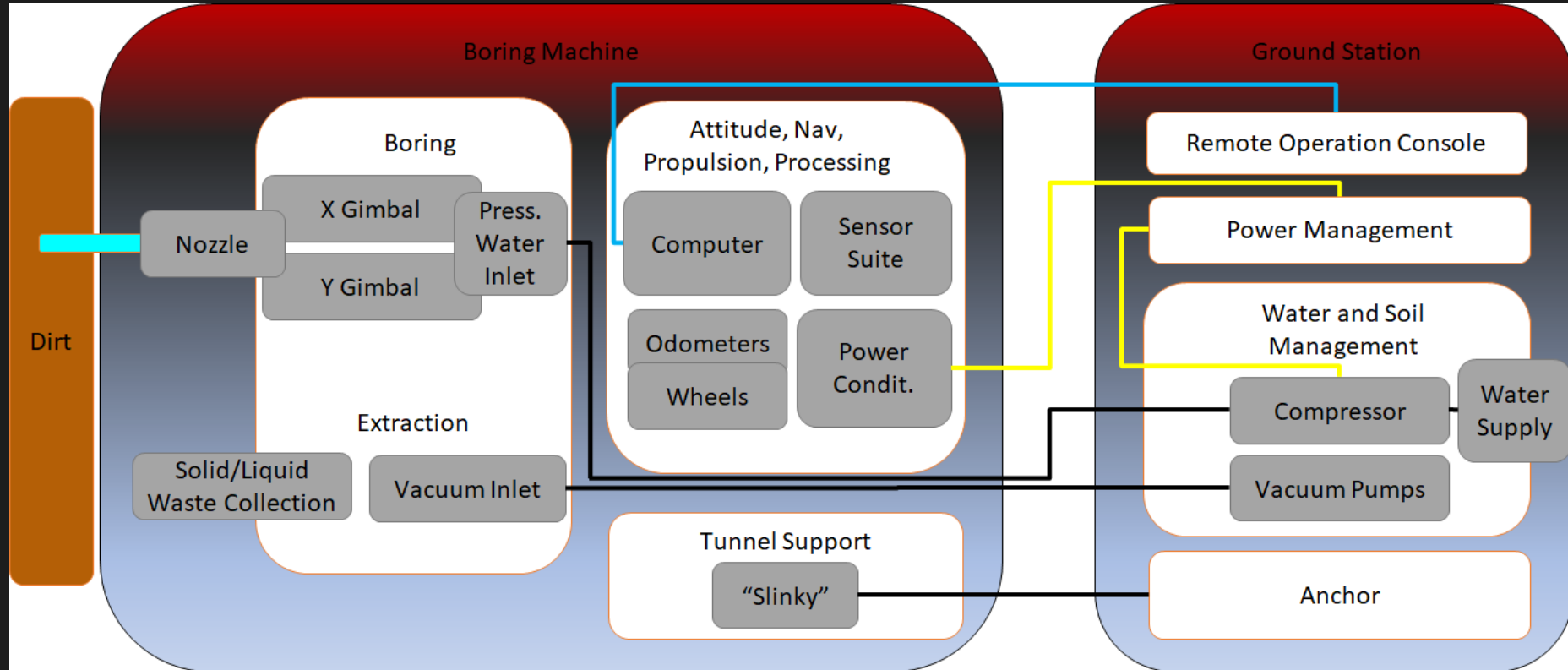


Engineering Budgets

Subsystem	Mass	Mass %
Navigation	6 lbs (2.7 kg)	2.5%
Propulsion	90 lbs (40.8 kg)	37.5%
Boring	15 lbs (6.8 kg)	6.25%
Spoils Removal	5 lbs (2.3 kg)	2%
Tunnel Support	28 lbs (12.7 kg)	11.7%
Structures	90 lbs (40.8 kg)	37.5%
Power	6 lbs (2.7 kg)	2.5%
TOTAL:	240 lbs (109 kg)	100%

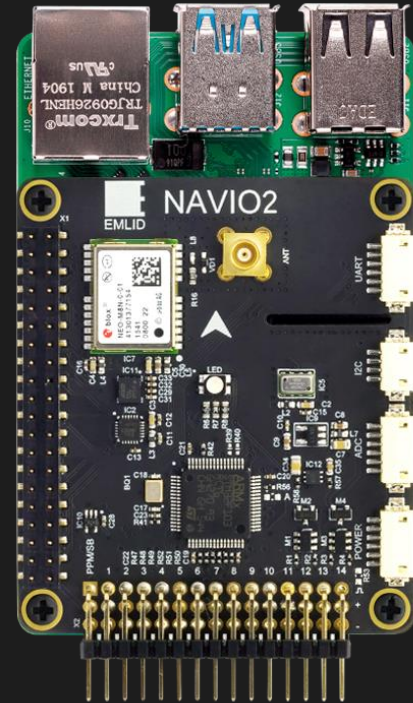
Subsystem	Max Power [kW]	% from Supply
Navigation	0.003 kW	0.003%
Propulsion	0.414 kW	0.41%
Boring	1.884 kW	1.9%
Spoils Removal	2 kW	2%
Tunnel Support	0 kW	0%
Structures	0 kW	0%
Power (losses)	4.3 kW (assume 50% worst case)	4.3%
TOTAL:	8.6 kW	8.6%

Functional Block Diagram



Navigation & Control

- Based on commercial off the shelf components
 - Raspberry Pi + NAVIO2 running ArduPilot
 - ArduPilot → Open Source autopilot firmware for unmanned systems including aircraft, rovers, and submarines
 - We will modify as necessary for our application (mix of rover/sub)
- Non-GPS navigation
 - Motor encoders on propulsion wheels
 - High accuracy IMUs with bias estimation
 - Barometer
 - Measurement teather
- Containerized Apps for specialized systems
 - Waterjet control
 - Database
 - Logging for errors/actions/telemetry
 - Data sent to filesystem



Sensors and State Estimation

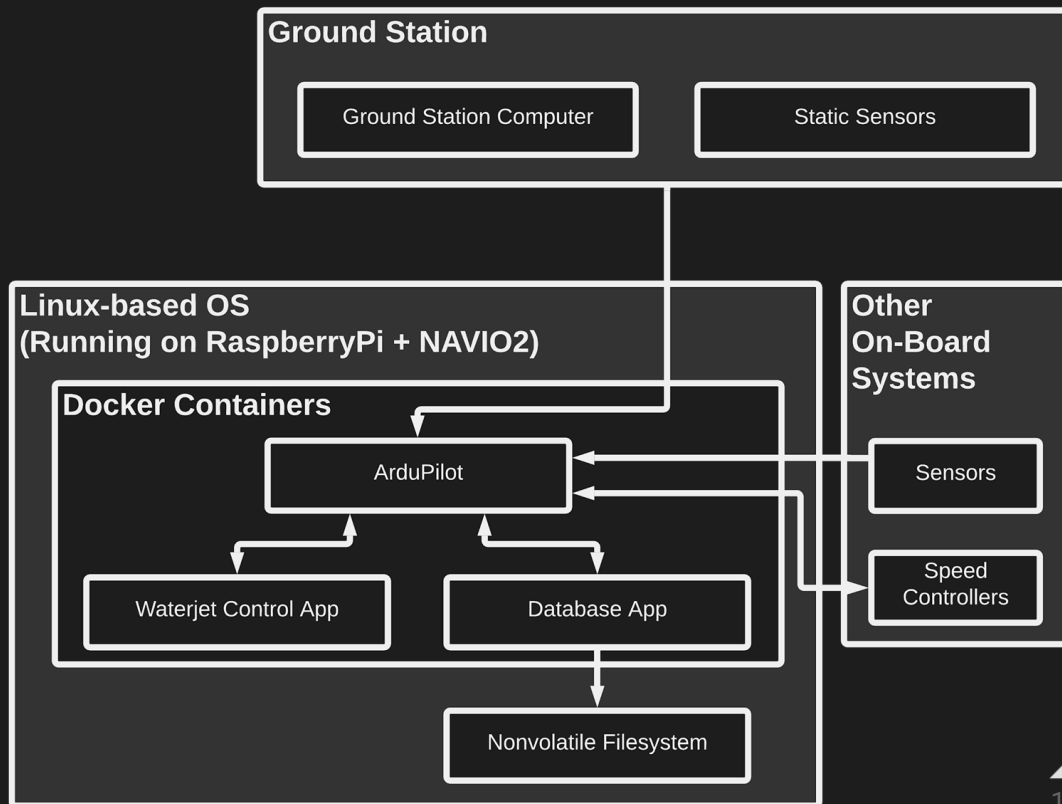
- Motor encoder
 - One per wheel
 - Measures linear distance traveled
- IMU
 - Triplet of IMU's allow for estimation of all three attitude directions based on gravity vector
 - Bias estimates included to reduce IMU drift
- Barometer
 - One on board, one at ground station
 - Allows for compensation of local pressure changes
 - Provides coarse depth estimate
- Tether Measurements
 - TBM pulls tether from ground station anchor
 - Measures linear distance traveled

ArduPilot:

- Employs dual internal Extended Kalman Filters for state estimation based on input sensors
- Team will test accuracy of off-the-shelf implementation to determine if additional custom filtering is required

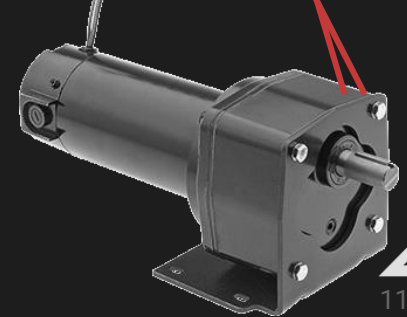
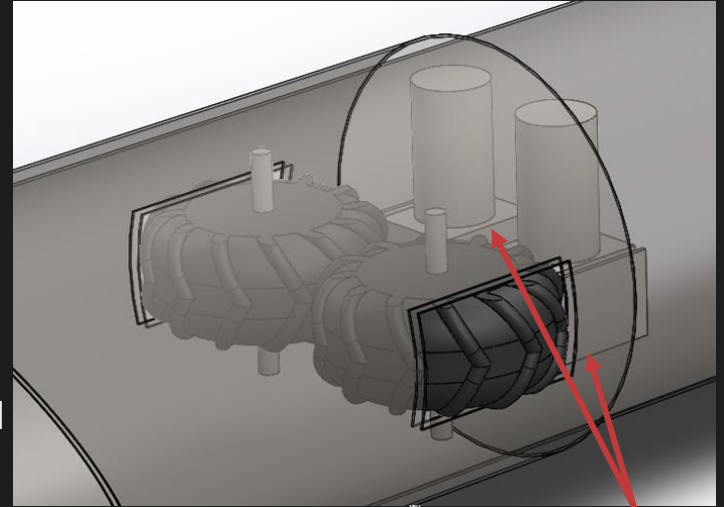
Software Architecture

- Three major elements:
 - Ground station
 - On-board computer
 - On-board sensors
- Primary control provided by ArduPilot (off the shelf but modified) and custom apps (Docker containers which interact with ArduPilot)
- Communication between ground station and on-board computer via Ethernet

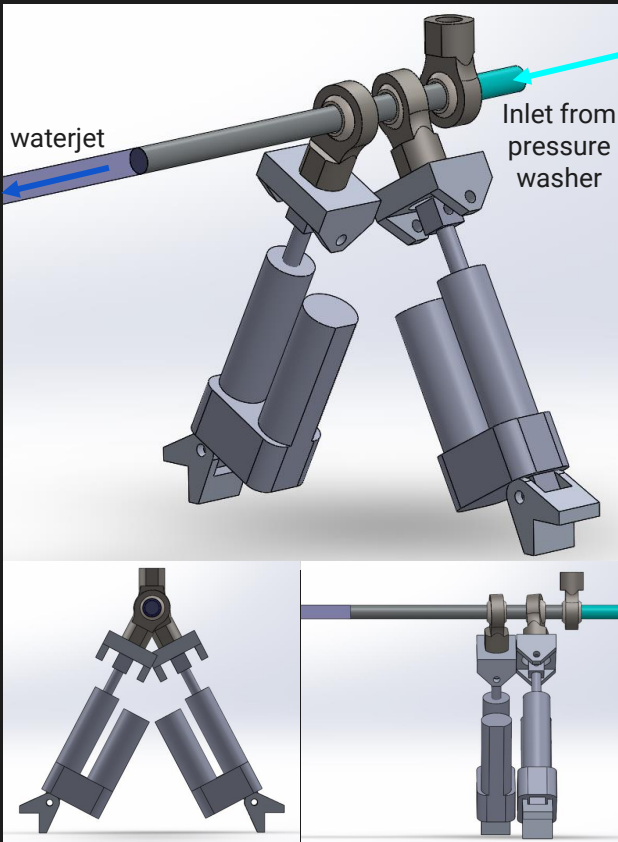


Propulsion

- Large wheels with “sand buggy” type treads
- Coupled to high torque DC motors
 - Currently evaluating McMaster 6470K61:
 - 90V DC, 2.3 A max
 - 560 in-lbs starting torque
 - 62 rpm max
 - Motors include sealed gearbox for torque increase
 - Additional torque can be obtained by utilizing external gears or chains when attaching to wheel axles
- Planning to test in soft (wet) dirt to determine wheel tread requirements
 - Softer/wetter → Larger treads
- Controlled using AC -> DC speed controller, AC input from supply



Boring Mechanism

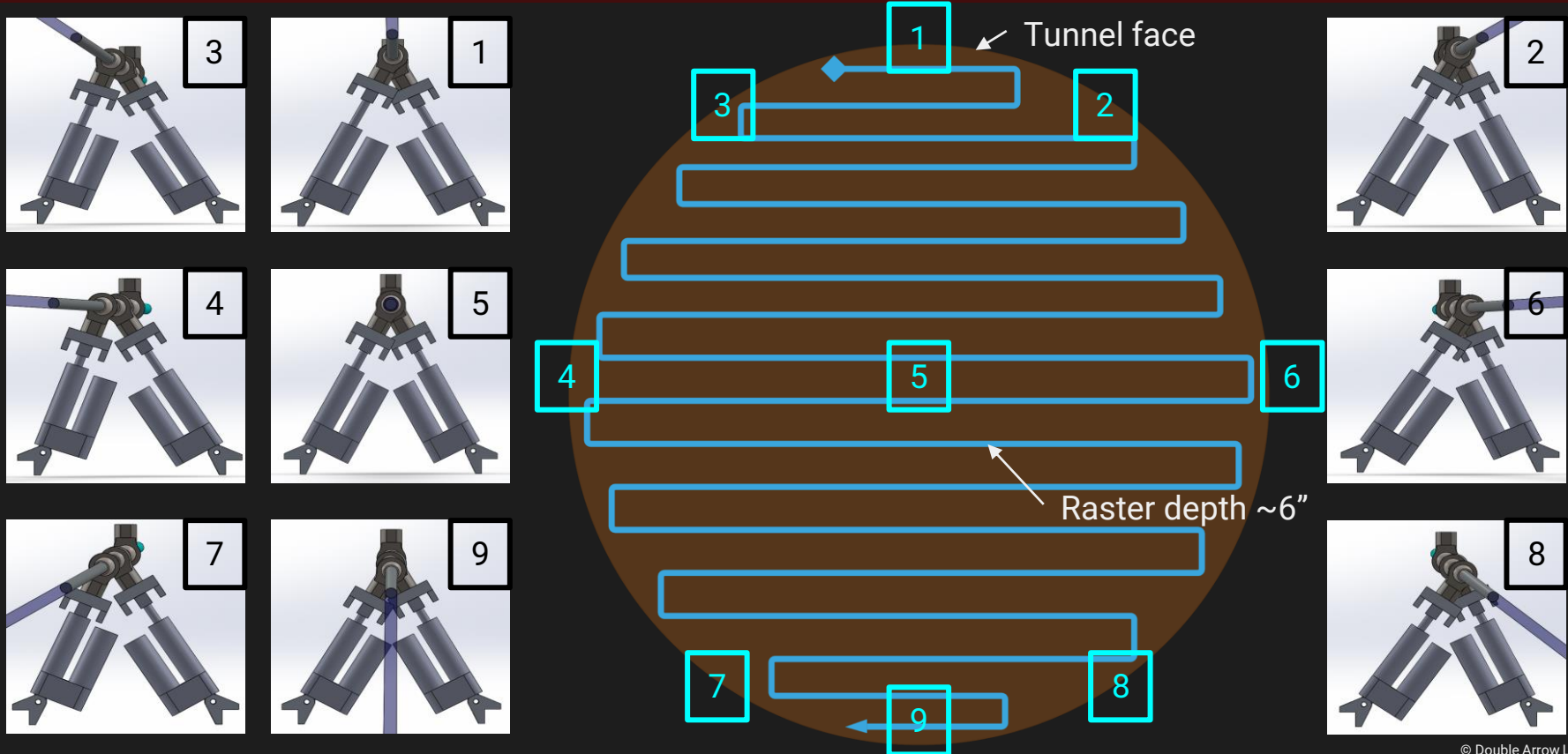


- 2-axis gimbal steers waterjet nozzle across tunnel face
- Linear actuators offset 90° would allow for full sweep of circular tunnel cross section
- Actuators shown have 2" stroke and are waterproof

Boring Process:

1. Nozzle rasters across tunnel face (next slide)
 - a. Raster removes ~6" of material, full face cleared in ~30 seconds
2. Vacuum sucks out water and dirt from tunnel
3. TBM advances to support new tunnel section

Nozzle Raster Process and Positions



Waterjet Testing Results



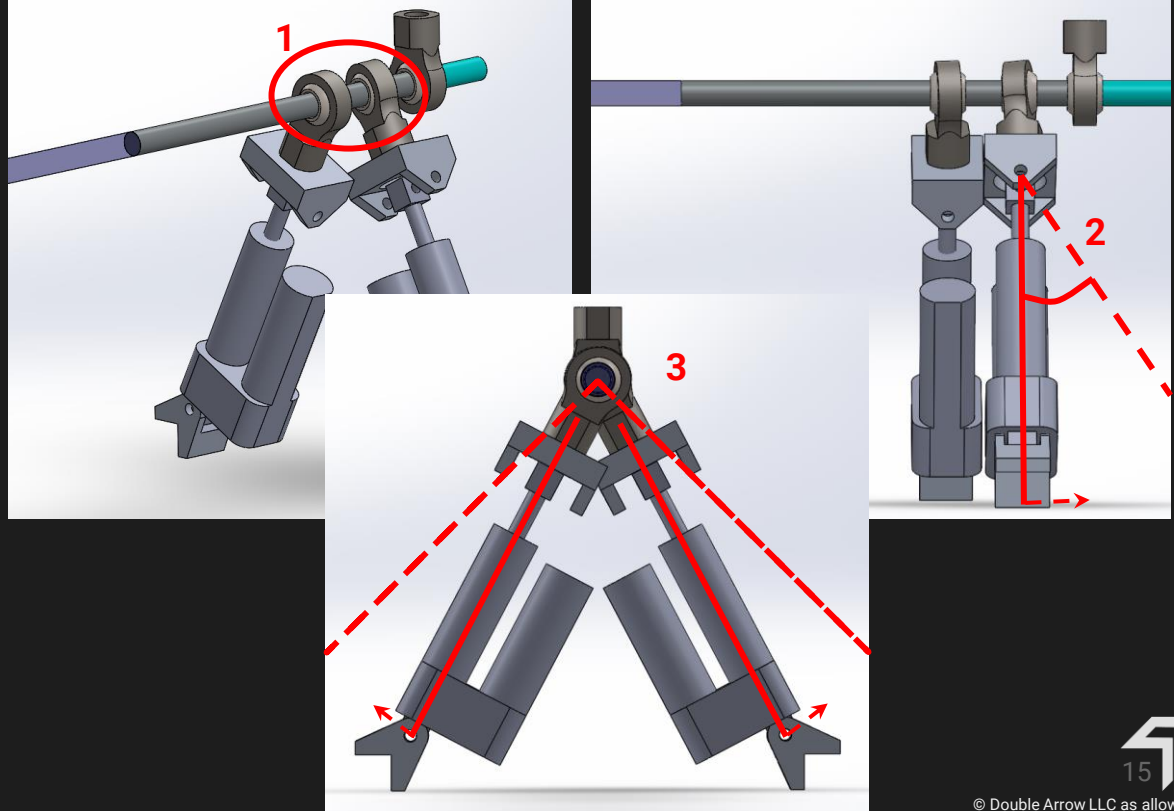
Test Results	
Nozzle Pressure	Estimated 2000 psi
Rastered Area	78.5 in ² ~25% of full scale
Bore Depth	Est. 8 in
Time	22 sec

Estimated boring rate: 0.007 ft/sec (0.138 m/min) - Approximately 2.3x faster than a snail
Full tunnel complete in approximately 4 hrs



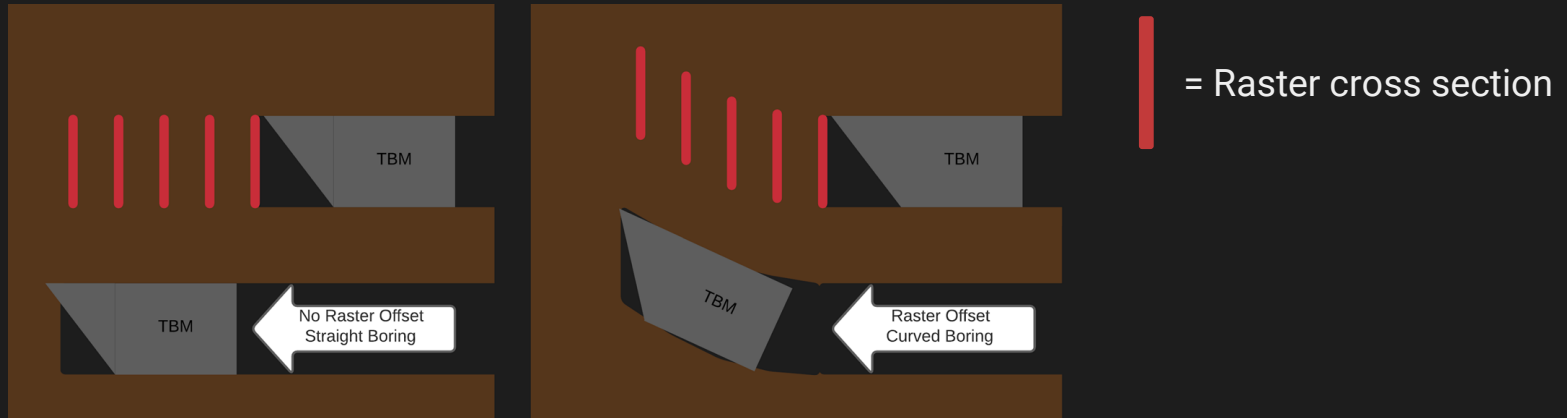
Planned Gimbal Redesign

1. Revisit swivel joints to allow for both actuators to impact direction changes about the same point
2. Trouble sourcing smaller actuators that meet requirements, angle backwards to accommodate larger stroke length
3. Redesign actuator mounts so they are actually 90° apart



Steering

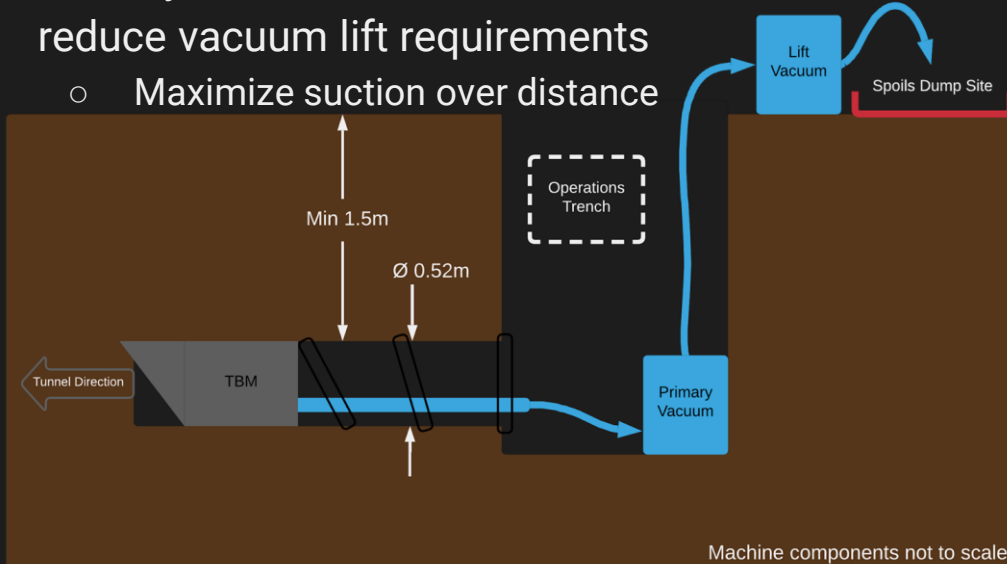
- Propulsion wheels provide uniform forward force to TBM
 - Lateral direction changes *could* be added using software and precise motor speed control
- Steering and general TBM attitude controlled by “path of least resistance” from the waterjet
 - Rastering offset left will cause the TBM to gradually turn left
 - Rastering offset up will gradually cause the TBM to pitch up



Spoils Removal

- Material removed using industrial wet/dry vacuum
- Primary vacuum operated and stored at the external ground station
- Primary vacuum will be installed at tunnel level to reduce vacuum lift requirements

- Maximize suction over distance



- Industrial vacuum selected as primary to ensure adequate suction over 30m tunnel
- Consumer shop vac can be used for lift vacuum due to minimal hose length and lift distance

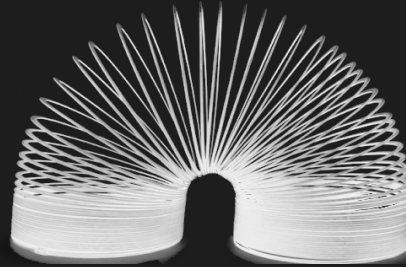
Spoils Removal Testing and Anticipated Changes

- Testing revealed resulting spoils are high viscosity, muddy
 - Concerns with clogging the vacuum line
- Solution: Saturate spoils with more water!
 - Reduces viscosity of spoils, resulting in steadier and more uniform flow
 - Increases overall flow rate requirement for vacuum, but current options are already overspec'ed



Tunnel Support in Concept

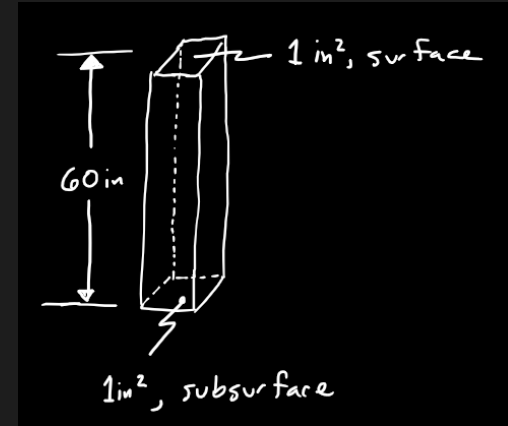
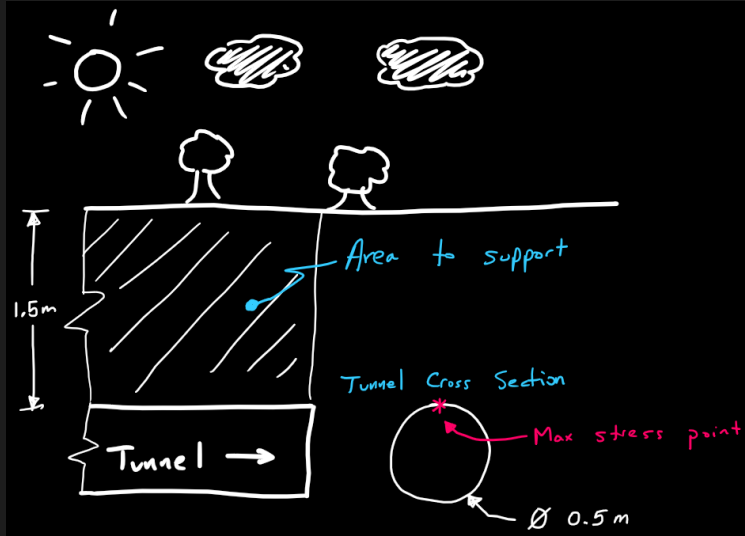
- Main support method based on a “slinky” concept
- Heavy duty tarp sewn between “slinky” loops to support dirt
- Made of sections of curved spring steel strips
- Compresses down to 1.5m, extends to 35m
- Full extension provides ~1m between loops
 - Loops provide support and tension for the tarp
 - Tarp supports any dirt that isn't supporting itself



Tunnel Support Analysis

Assumptions:

- Dirt density = 1500 kg/m^3
- No rocks or large variations in density/composition
- Maximum stress at top of tunnel (1.5 m underground)

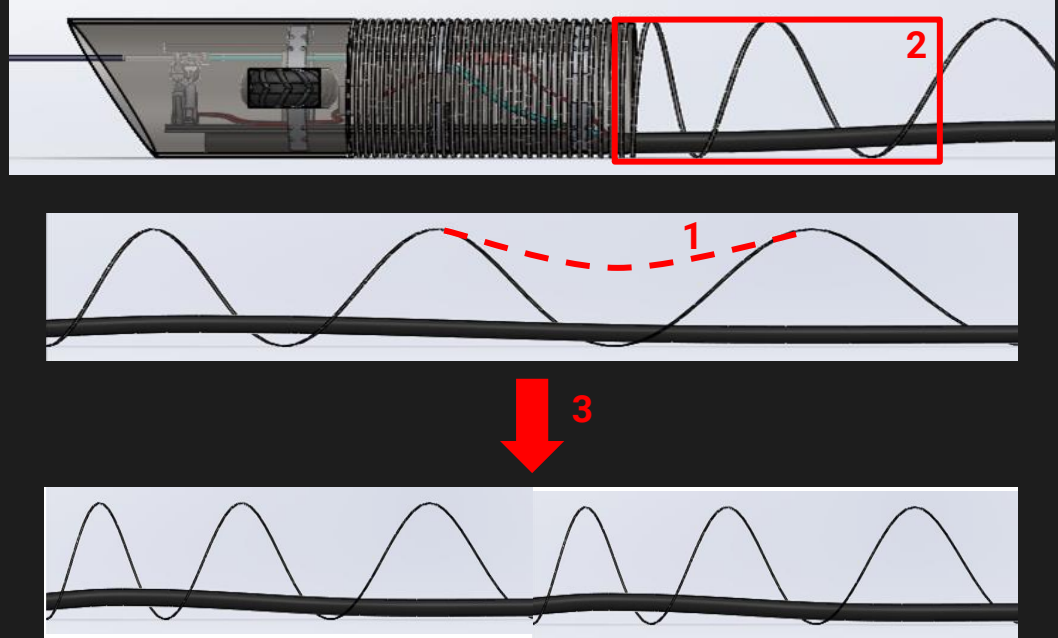


Volume in a column of dirt:
 $60 \text{ in}^3 = 10^{-3} \text{ m}^3$

Pressure at Max Stress:
 $3.3 \text{ psi} = 22.7 \text{ kPa}$

Planned Tunnel Support Redesign

1. Investigate fabric materials to support dirt
 - a. 3.3 psi isn't much, but at 1 m spans, there's ~2,500 lbs of dirt
2. Extend TBM to allow for slinky to fully expand before supporting tunnel
 - a. This will ensure cave-ins won't occur when the tarp isn't fully expanded
3. Consider lower pitch helix to reduce free span between supports



Stored Energy

- Single cell battery included on board to provide emergency power for shutdown and safing in the event of an emergency
 - Main system power will be supplied through an umbilical connected to an external power distribution system and The Boring Company's provided AC supply line
- Team is currently analyzing forces in coiled tunnel support structure to determine if alternate design is needed



External Power Station

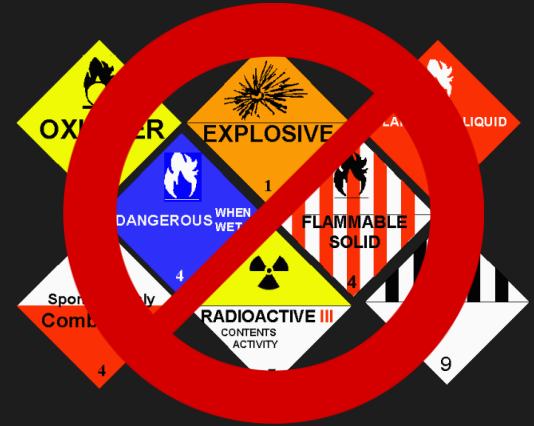
- ▶ Planning to step down provided power at the ground station
 - Input: 480 VAC @ 60 Hz
 - Output: 120 VAC @ 60 Hz
- ▶ Some 120 VAC lines will power components at the ground station
 - Ground station computer
 - Pressure washer
 - Spoils removal vacuums
- ▶ Rest will be sent to the TBM via an umbilical
 - 120 VAC input to TBM
 - On-board power converters convert to req'd levels
 - 120 VAC passthrough for propulsion speed controllers
 - 12 VDC for linear actuators (waterjet gimbal)
 - 5 VDC for on-board computer



480 VAC -> 120 VAC Transformer

Hazardous Materials

- Does not currently include any materials classified as hazardous
- High pressure water supplied to nozzle through commercial off the shelf pressure line
- Pressurized using commercial off the shelf power washer



Hose pictured (left) is 30m in length and rated to over 2x MAWP of pressure washer output

Major Safety Features



Example monitoring in ArduPilot

- RC connection monitoring
 - Can pre-program behavior upon loss of connection
 - Typical behavior: Return to Home
 - In our application: Safe all systems and stop boring
- Temperature monitoring
 - Motors
 - Batteries
 - Processors
- Gas sensor
- Safety features implemented through ArduPilot