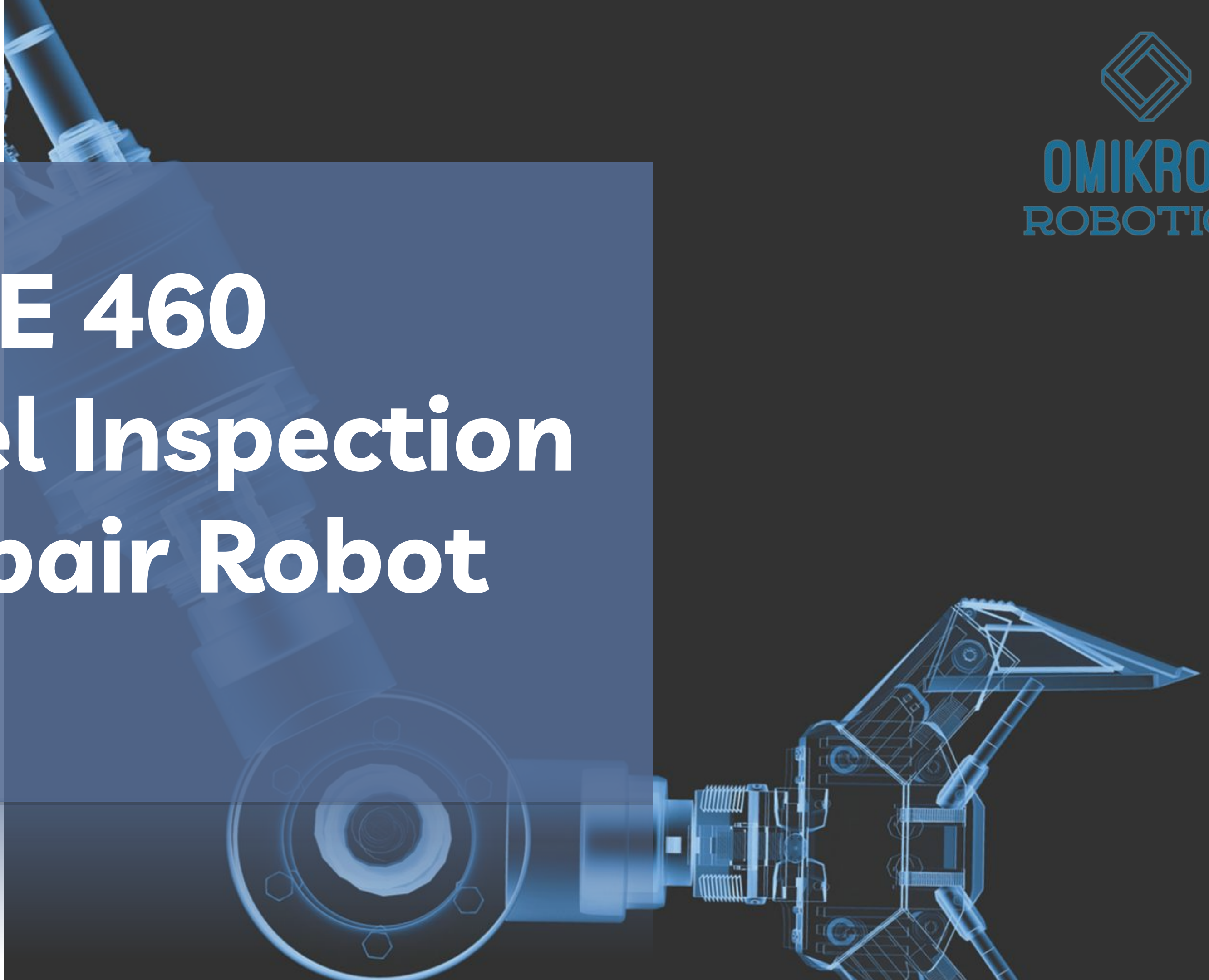


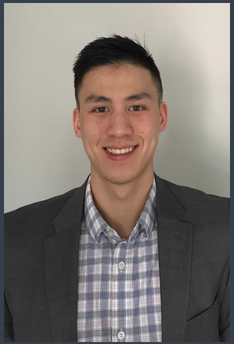
MEC E 460 Vessel Inspection & Repair Robot

April 8, 2021

OMIKRON ROBOTICS

DESIGN TEAM

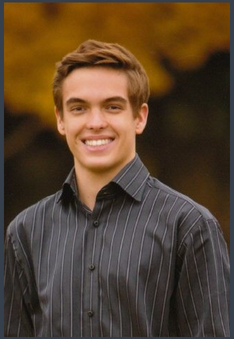
George Felobes



Calvin Chen

Areej Khaddaj

Kenny Okeke



Liam Wolf

Eric Wong

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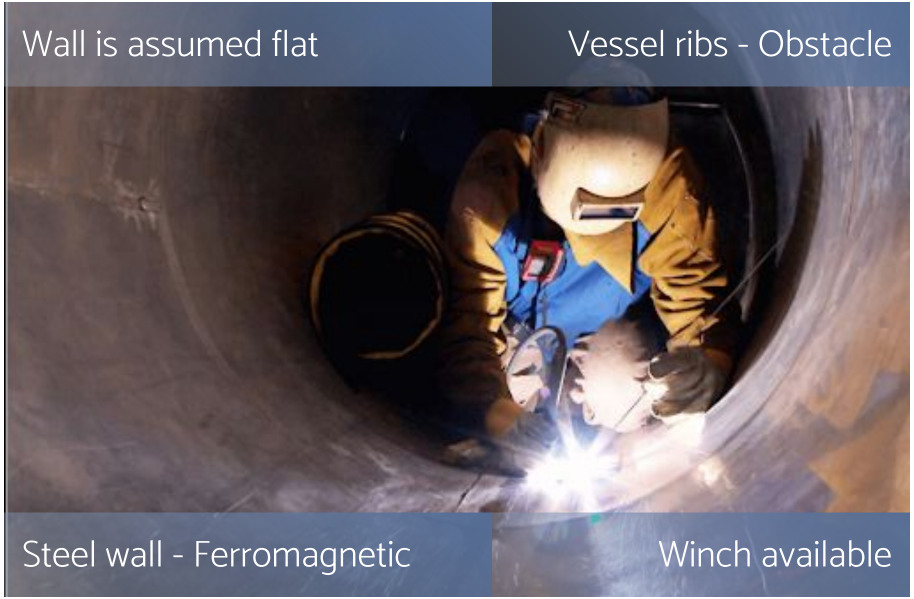
Objective

To design a modular robotic system that fits through a vessel entrance to carrying out inspection and repair tasks.

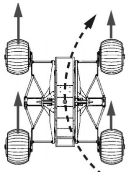
Motivation

1. Inspection and repair tasks are time consuming and difficult
2. No available solution on the market for large scale inspection and repair
3. Confined spaces pose significant risks to personnel



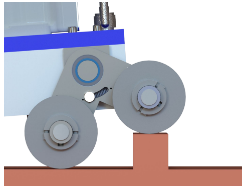
Source from: Irwin, C., 2018. Assess job sites for unexpected confined spaces. [online] Ishn.com. Available at: <https://www.ishn.com/articles/108937-assess-job-sites-for-unexpected-confined-spaces>

2 - Design Specifications



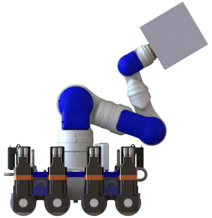
Maneuverability

The robot must be able to travel along horizontal and vertical surfaces, and rotate about its own axis.



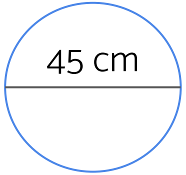
Obstacles

The robot must overcome 7.6 x 7.6 cm (3” x 3”) ribs that span the circumference of the vessel.



Payload

The manipulator arm must be able to support a 20 kg payload and have at least 5 DOF.



Size

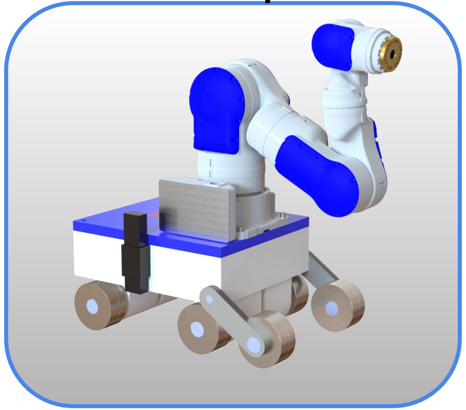
Each module must be able to fit within a 45 cm diameter hole.

Rigidity

The robot must become rigid when performing inspections/repairs.

2 - Concept Designs

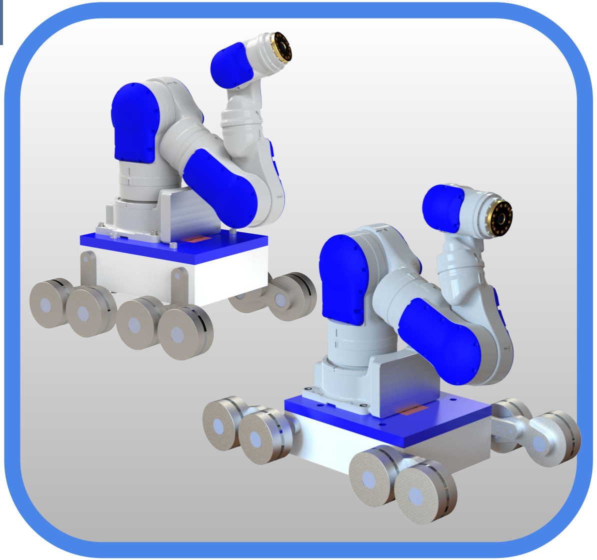
High Clearance Concept



- Active wheels: 4
- Obstacles: High clearance
- Other features:
  - 2 passive wheels
  - Actuator magnets

Score: 193/255

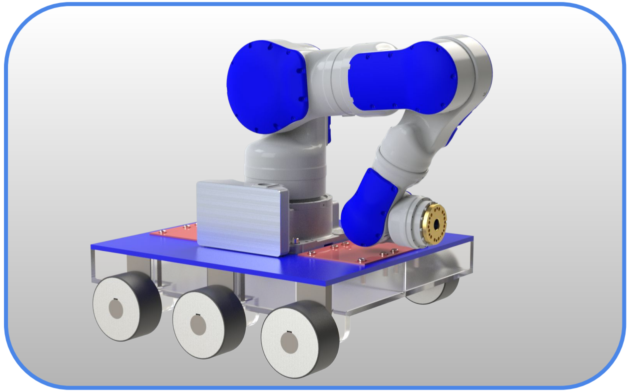
Pivot Platform Concept



- Active wheels: 8
- Obstacles: Change robot height
- Other features:
  - Base permanent magnets
  - Lowered position provides lower COM for stability

Score: 236/255

Crawler Concept

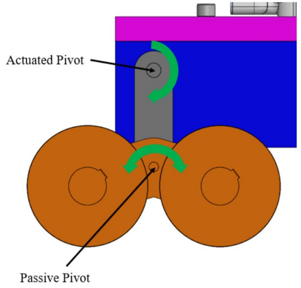


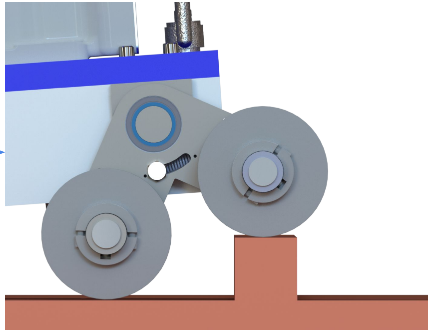
- Active wheels: 6
- Obstacles: Staggered wheels with independent suspension system
- Other features:
  - Suspension system
  - Wide base

Score: 210/255

3 - Designs Change

Simpler Rocking Mechanism



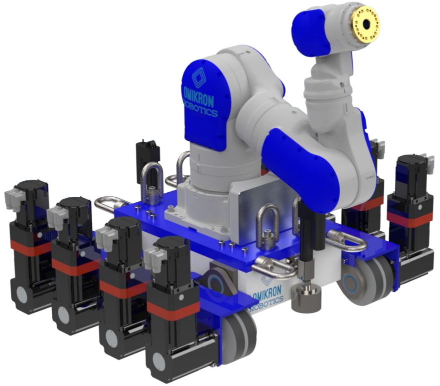


Due to feasibility of the design, The pivot-rocking system is replaced with the rocking mechanism

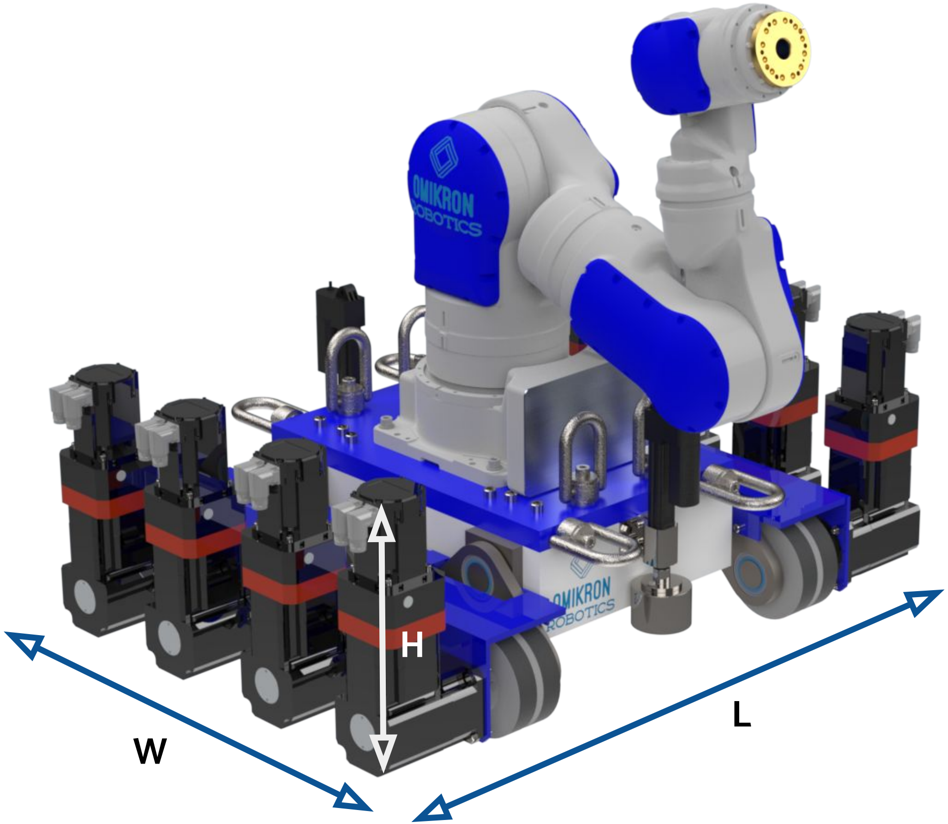
- Removes the additional degree of freedom
- Able to easily traverse 7.6 cm (3”) ribs

Concept 2

Solution



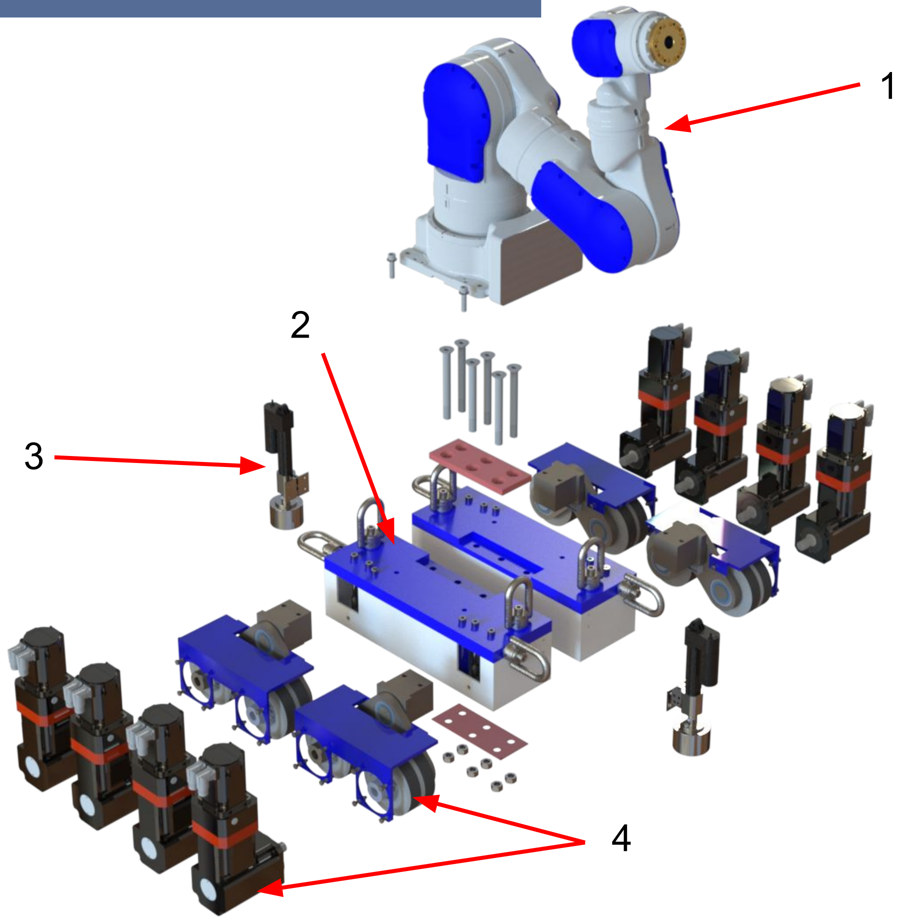
3 - Solution



Chassis Dimensions: (LxWxH): 110.4 X 82.5 X 42.1 cm

Robot Mass: 500 Kg

3 - Subsystems

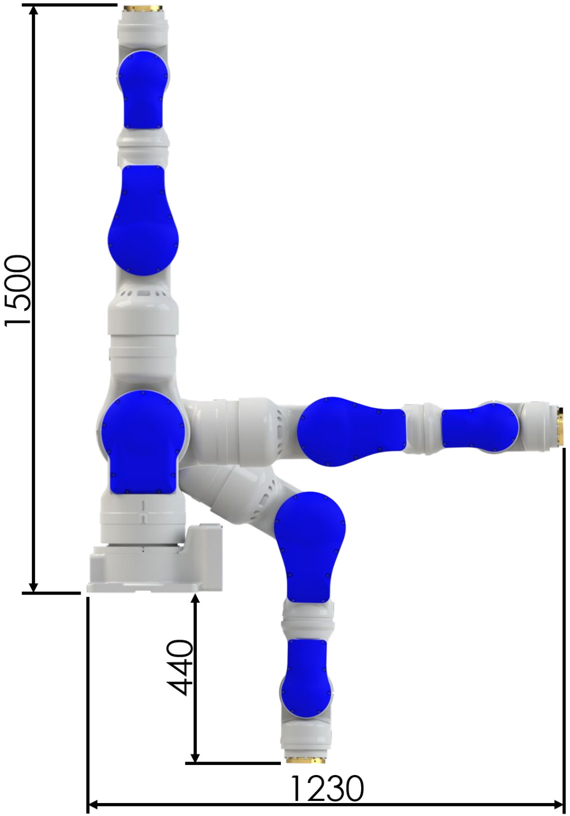


Modular Sub-Systems:

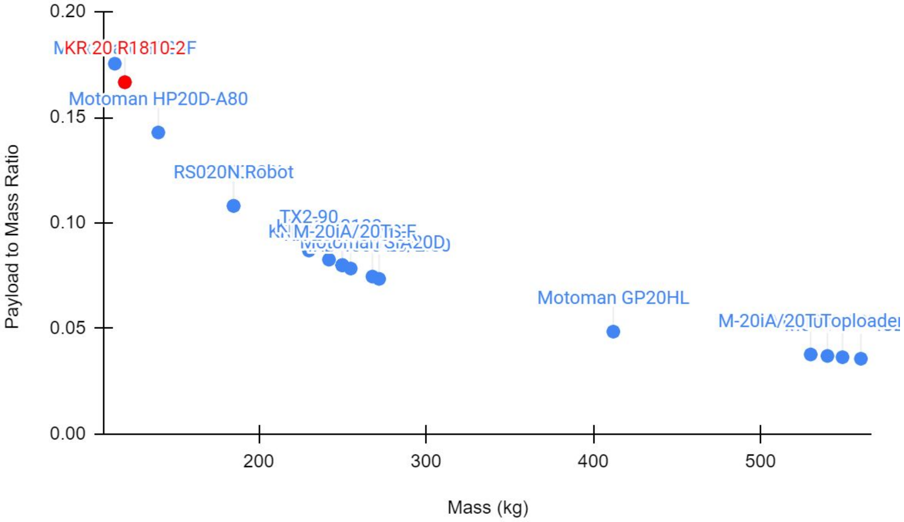
1. Manipulator
2. Modular Chassis
3. Actuated Permanent Magnets
4. Pivot Drive system

3 - Manipulator

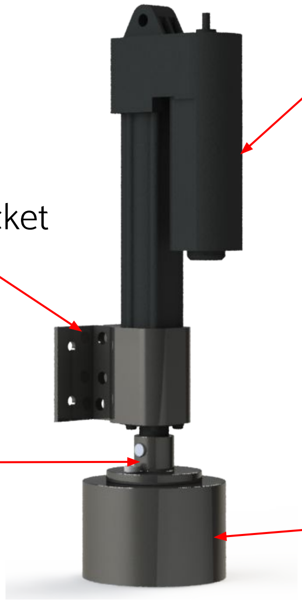
OMIKRON ROBOTICS



- Yaskawa MOTOMAN SIA20F
- 7 DOF
- 20 kg Payload
- 120 kg Mass
- 0.17 Payload to Weight Ratio

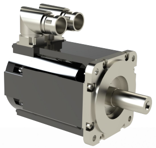


3 - Linear Actuator



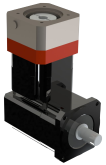
- The linear actuator is used to deploy an electronically controlled permanent magnet.
- Provides additional rigidity during inspections/repairs.

3 - Drive System



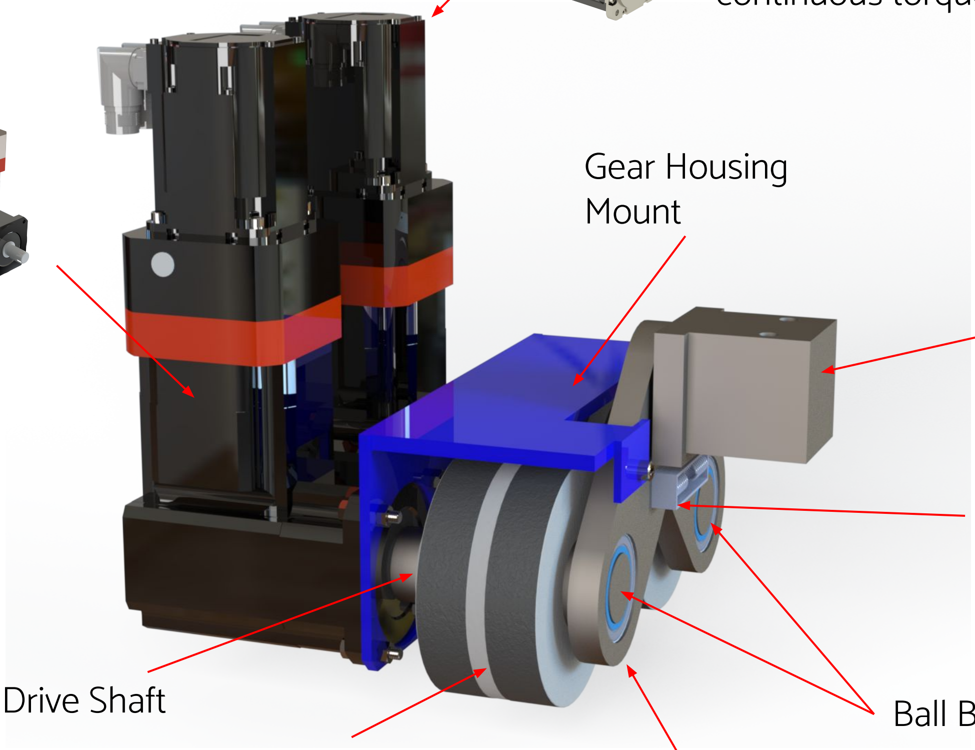
AKM2G-41D Servo Motor

Servo Motor with maximum continuous torque of 2.85 Nm

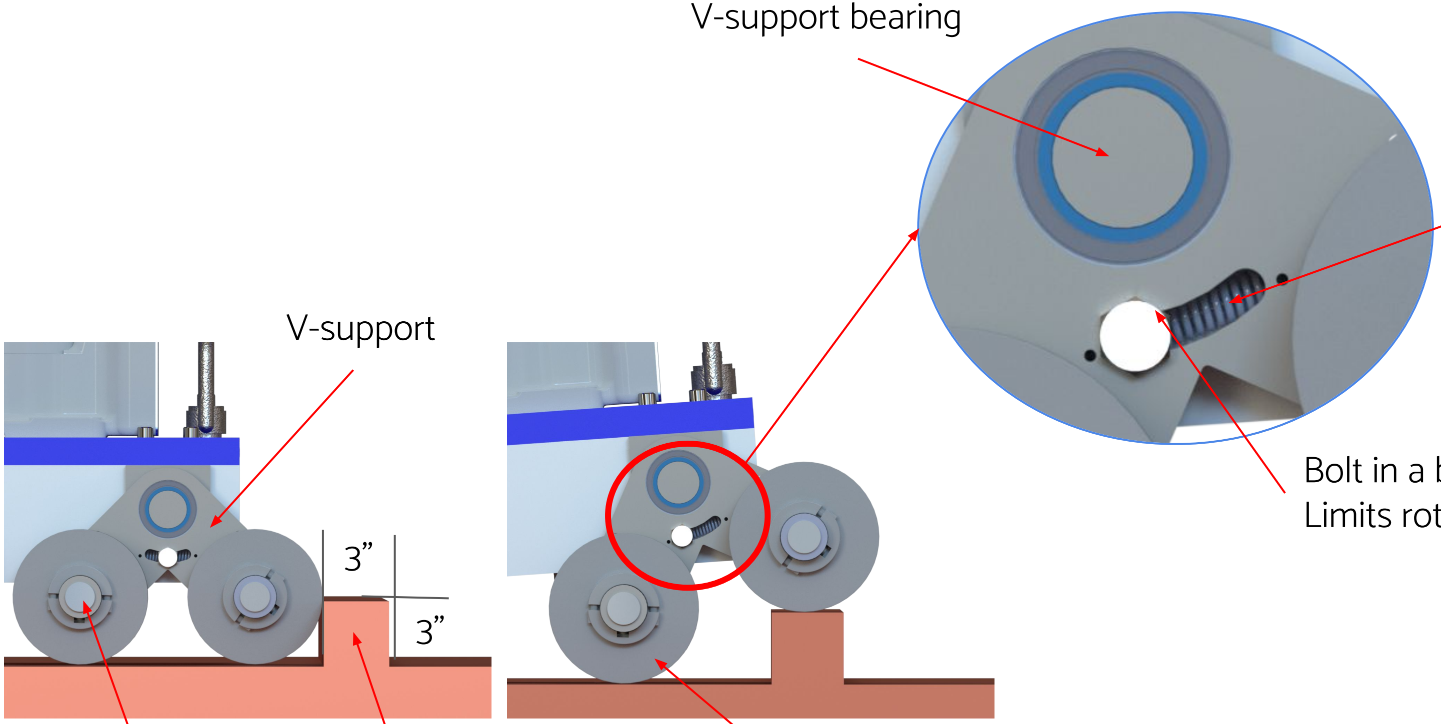


DTR-115-100 Gearhead

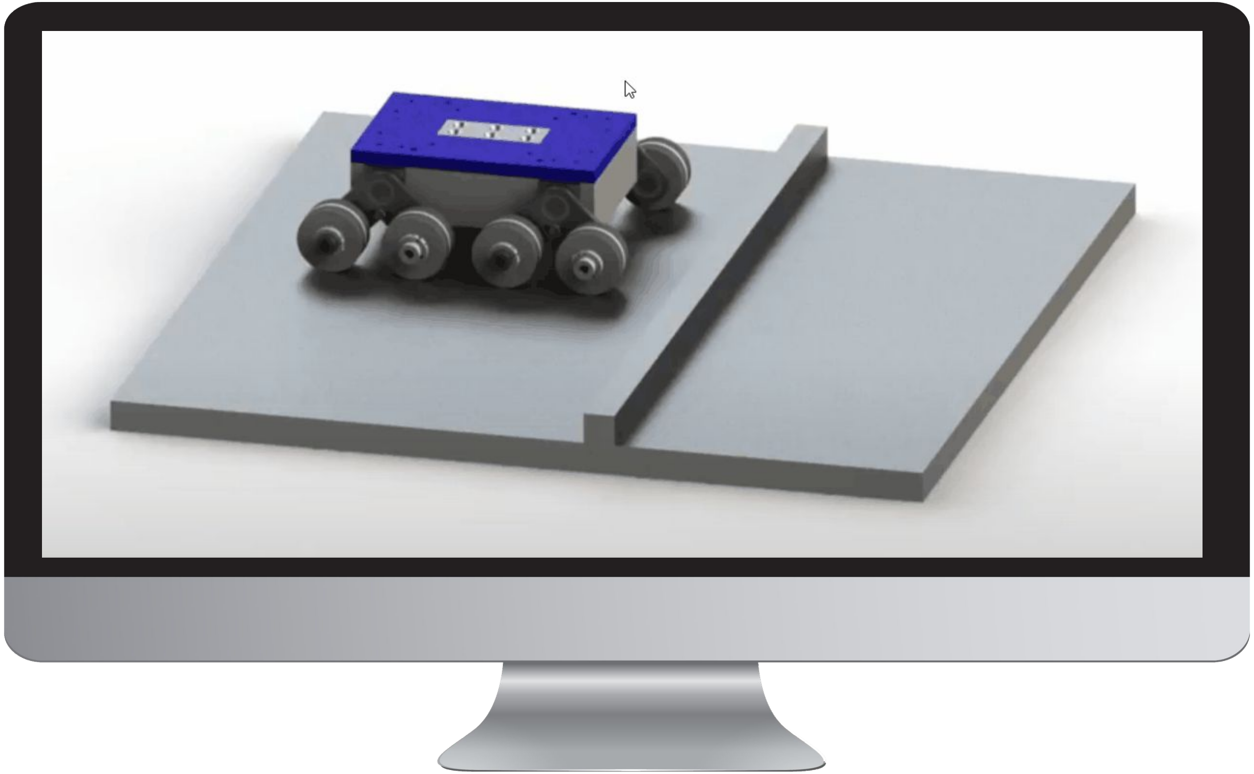
- Right angle planetary gearhead
- Rated for 185 Nm continuous torque
- 100:1 Gear ratio



3 - Pivot Mechanism



3 - Motion Analysis

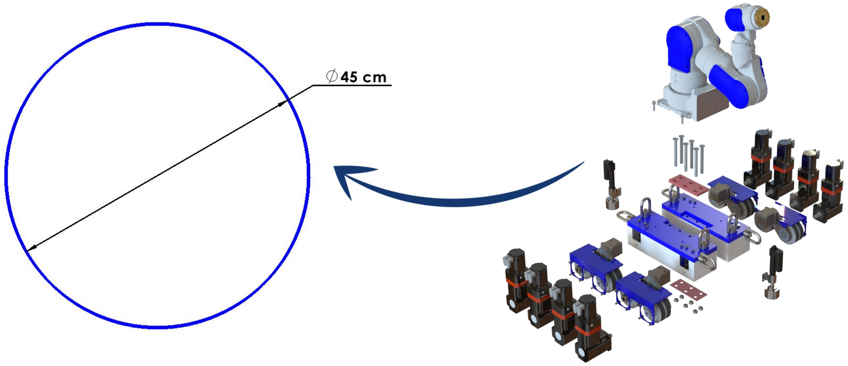


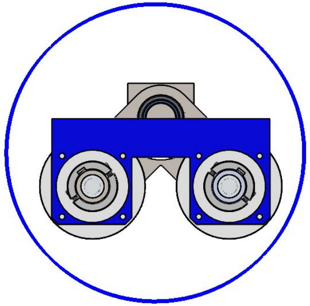
Simple animation of the robot traversing a 3 in x 3 in rib.

The solution is simplified to the chassis and suspension due to computational constraints

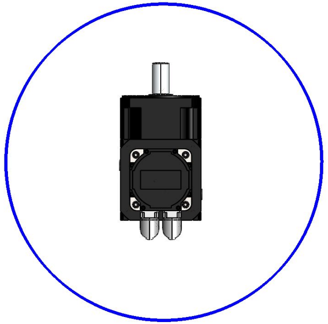
Magnetic adhesion of the wheels will allow the wheels to climb up and down the rib

3 - Sub System Modularity

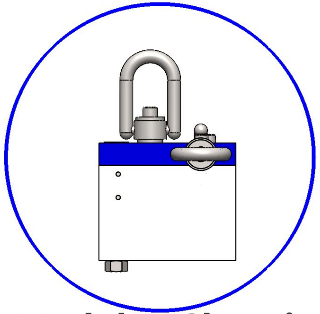




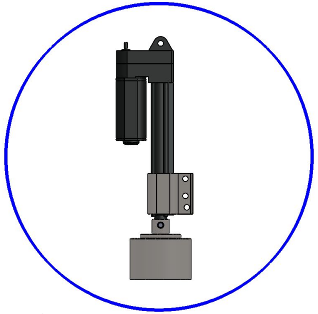
Wheel System



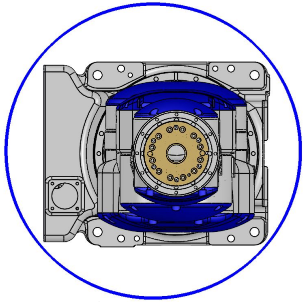
Motor & Gearhead



Modular Chassis



Linear Actuator

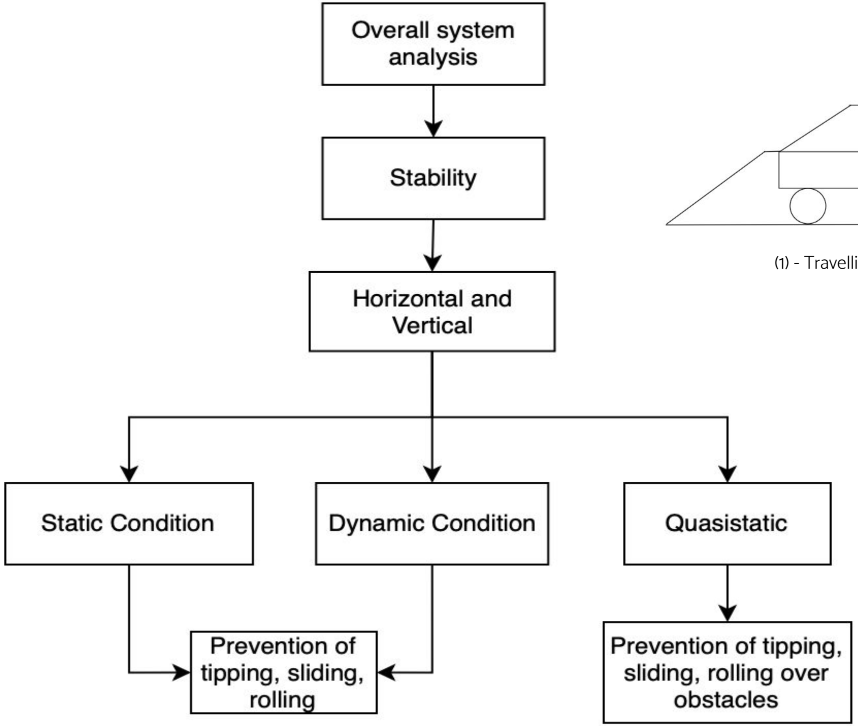


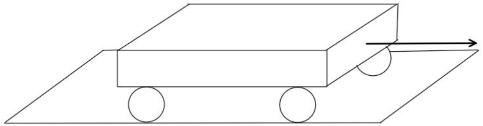
Manipulator

OVERALL SYSTEM ANALYSIS

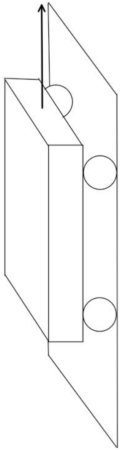
4

4 - Analysis Flowchart

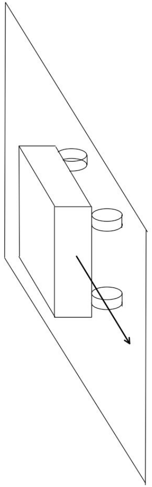




(1) - Travelling on flat ground



(2) - Vertical travelling on wall



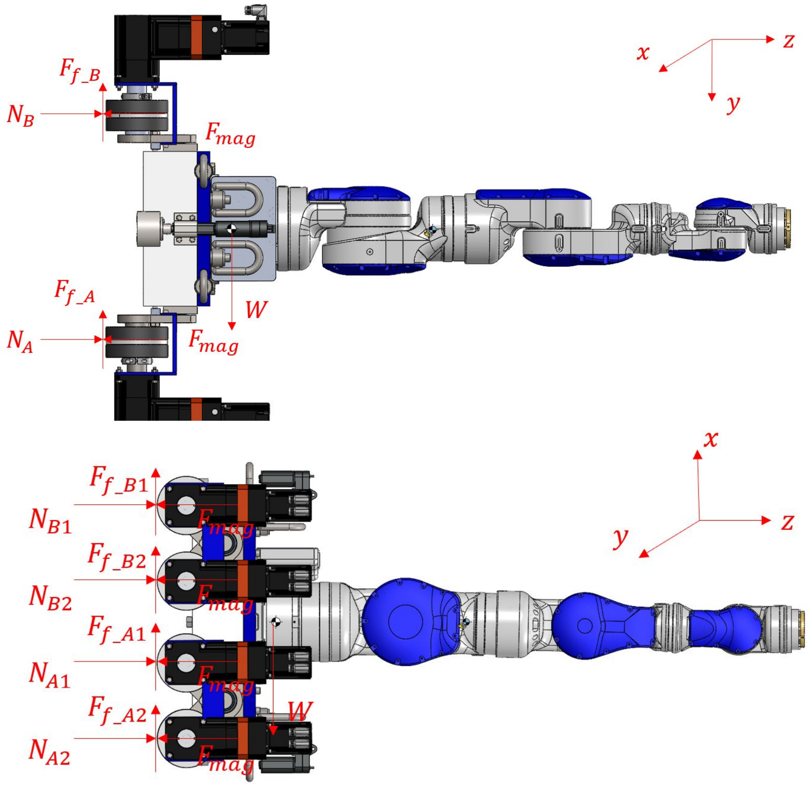
(3) - Horizontal travelling on wall

"Static condition" - Robot + manipulator are stationary

"Dynamic condition" - Robot stationary while manipulator arm moves

*Robot moving is considered to be quasi-static due to low, constant velocity (~250 mm/s)

4 - Static Stability

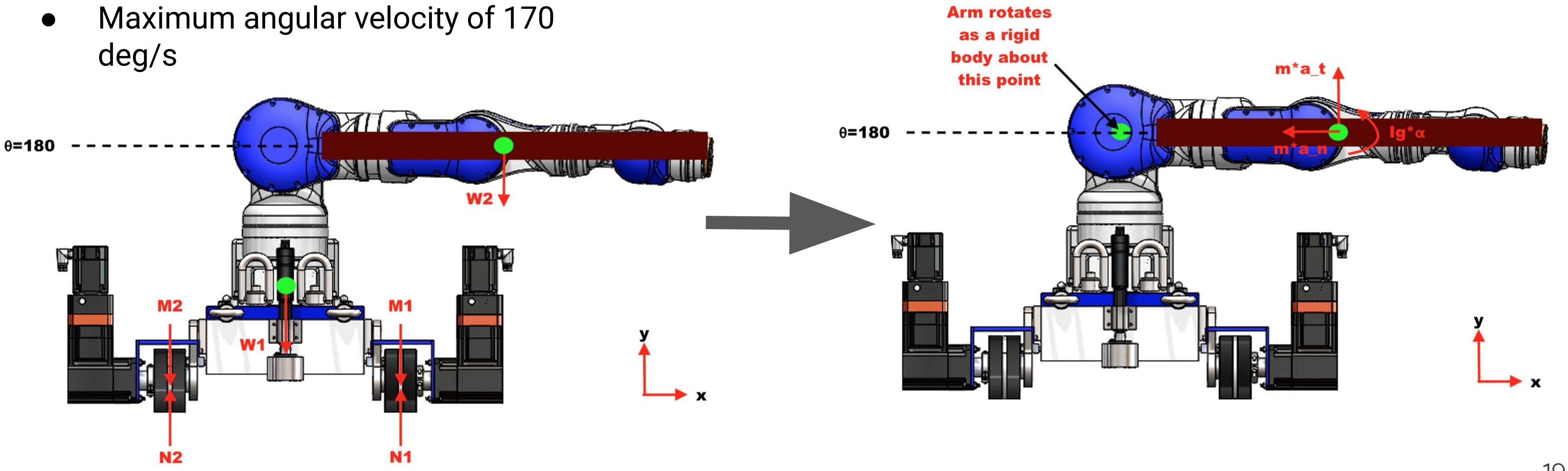


- Zero motion.
- Horizontal orientation on the wall is the worse case for sliding.
- Vertical orientation on the wall is the worse case for tipping.
- Neither tipping nor sliding occurs.

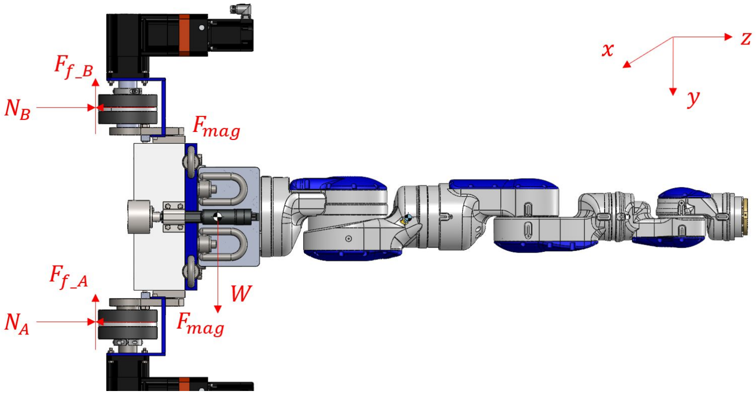
4 - Dynamic Stability

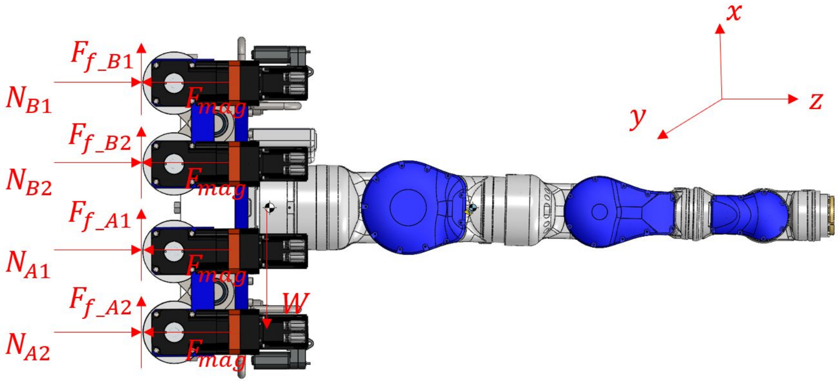
Derivation of dynamic forces:

- Approximation of manipulator arm as a rigid rod
- Rotates about base, reaching maximum velocity at 180 deg
- Maximum angular velocity of 170 deg/s



4 - Dynamic and Quasi-Static



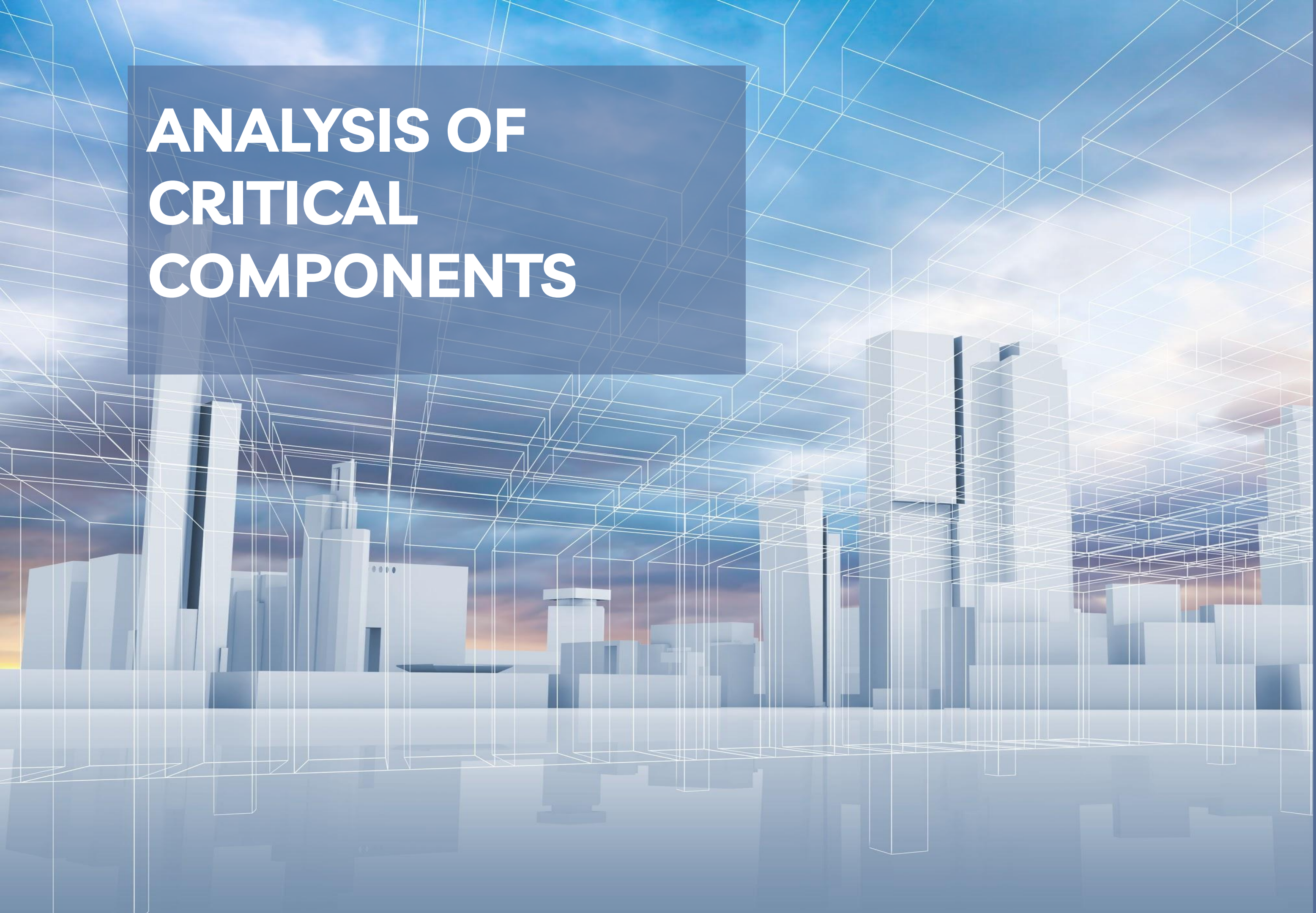


- Dynamic case: Arm moves, while robot is stationary.
- No contact between arm and vessel.
- No tipping or sliding occurs.

- Quasi-static case: Robot is moving over obstacle, arm is stationary.
- No tipping or sliding occurs.

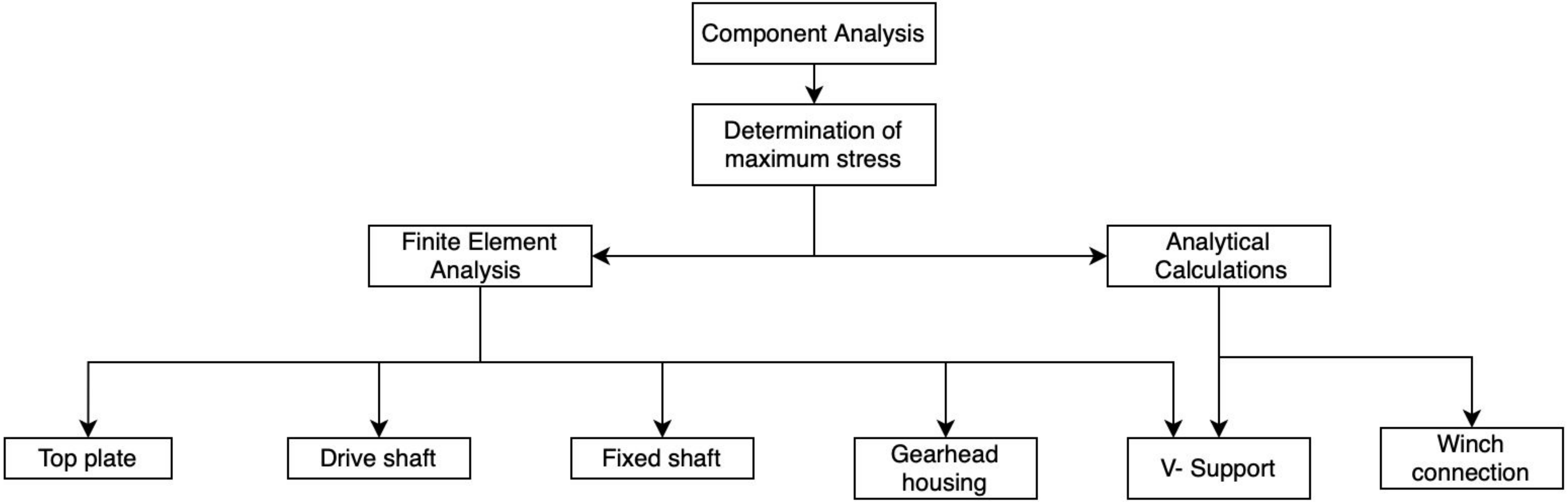
	(2) - Vertical travelling on wall	(3) - Horizontal travelling on wall
Minimum Normal Force Required (N)	**612**	1116
Traction (N)	5597	**5400**

ANALYSIS OF CRITICAL COMPONENTS



5

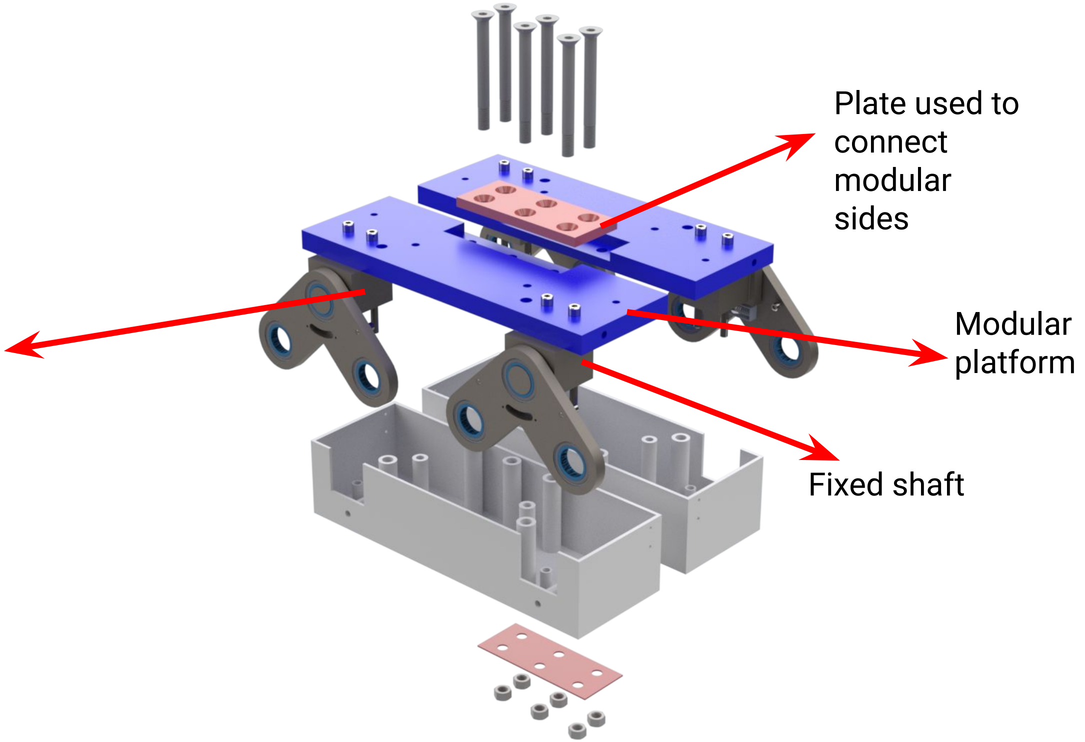
5 - Component Analysis Flowchart



5 - Chassis

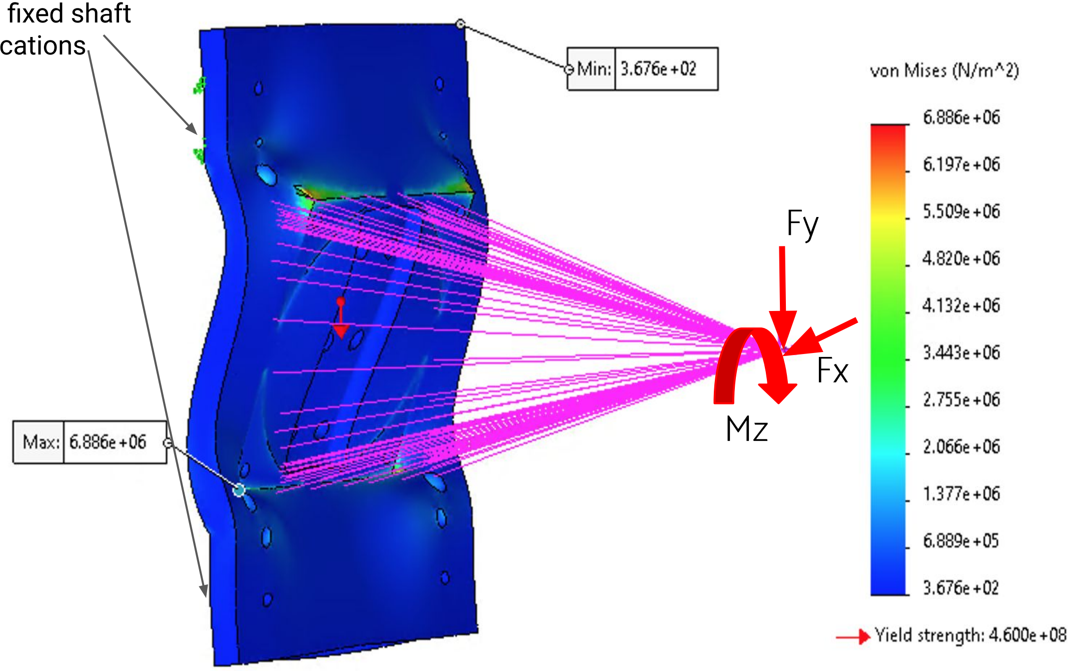
Loading conditions are negligible for the chassis.

Fixed shaft and drive system is connected directly to the platform, supporting the load due to manipulator. Therefore, loading conditions on chassis are negligible.



5 - Top Plate

Rigid connection at fixed shaft locations



Previously derived dynamic forces are modelled as remote loads on manipulator plate.

Cases considered:

- Static (horizontal/vertical)
- **Dynamic (horizontal/vertical)**

FOS: 66

5 - Drive System FEA

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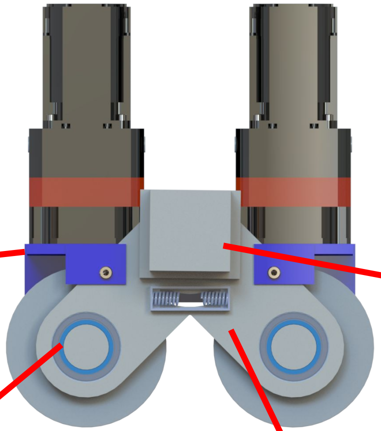
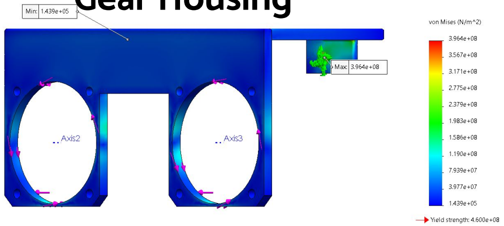
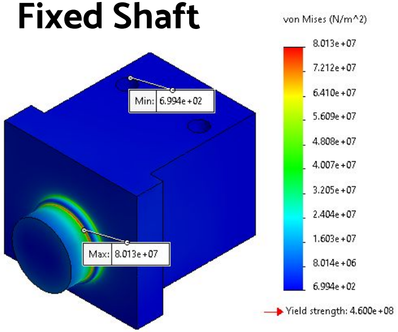


Gear Housing



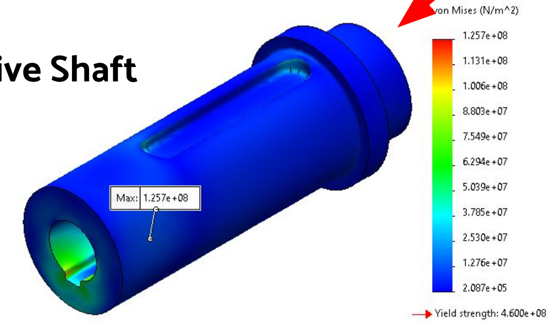
FOS: 1.2

Fixed Shaft



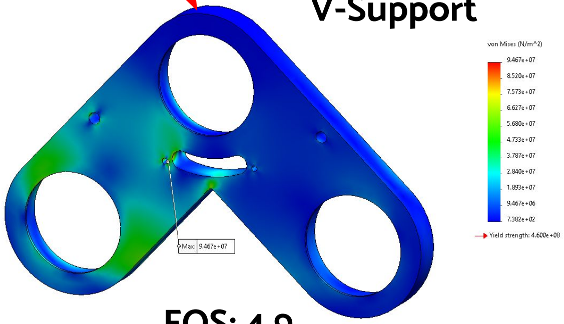
FOS: 5.7

Drive Shaft



FOS: 3.6

V-Support



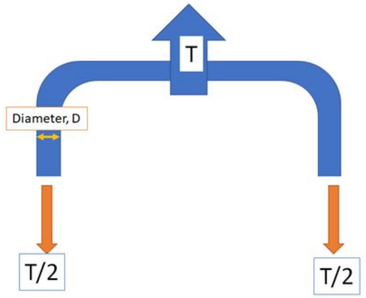
FOS: 4.9

No Impact or Buckling

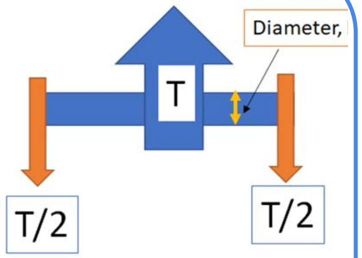
General Assumptions:

- 4130 Steel
- Linearly elastic and isotropic

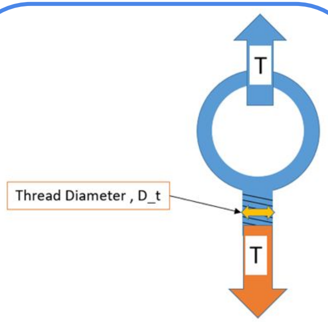
5 - Winch Connection



Tensile



Shear



Thread Strength

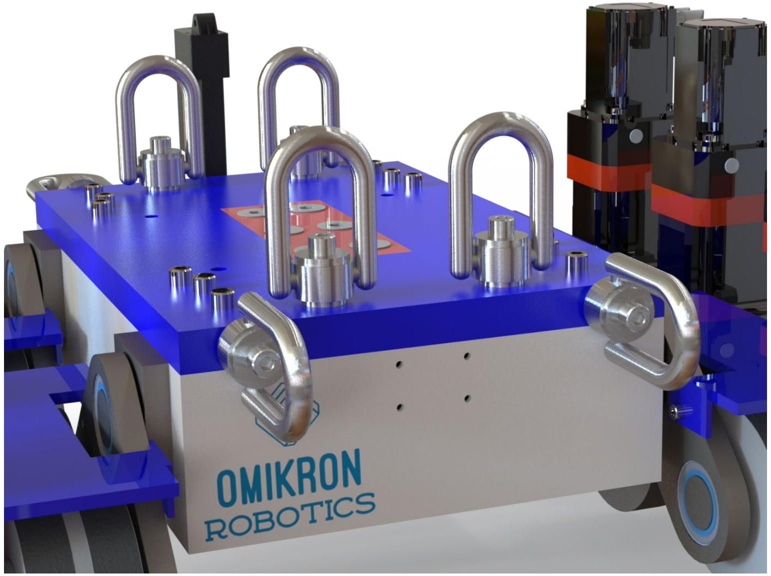
<u>Manufacturer Specifications:</u>

- Steel Hoist Ring McMaster-Carr 2994T91
- Rated for 1334 kg (2,500 lbs) vertical lifting capacity
- Rated for 756 kg (1,667 lbs) at 45° lift angle from vertical

<u>Analytical Calculations:</u>

- Axial Loading - Does not fail
- Shear - Does not fail
- Thread Strength - Does not fail

FOS: 2.0



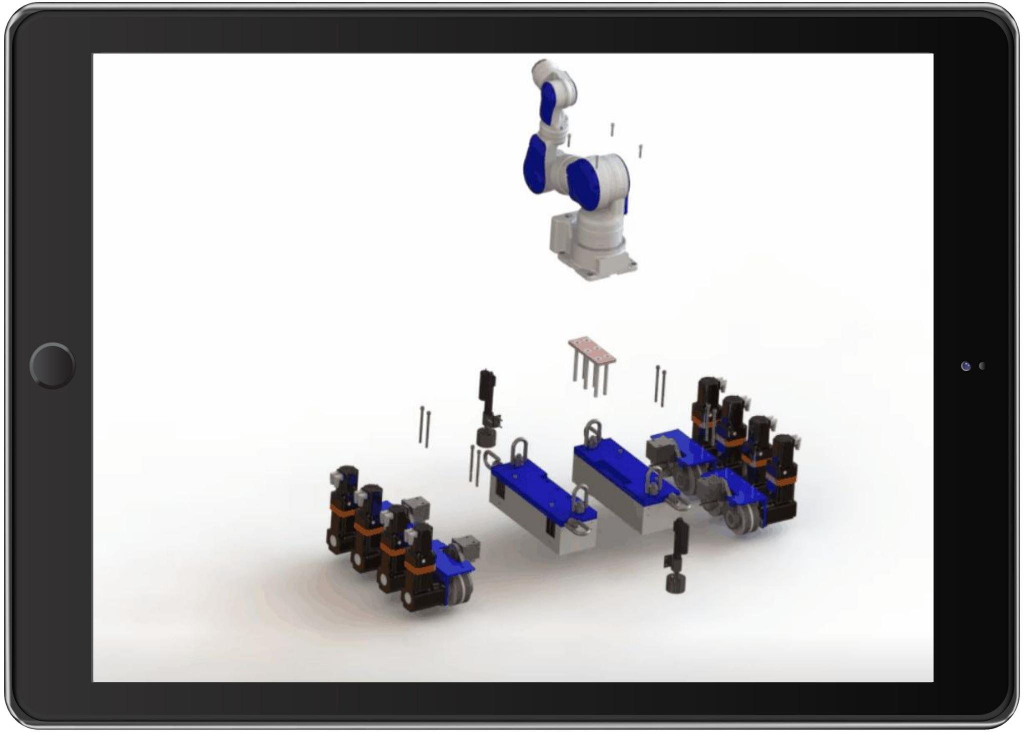
ASSEMBLY AND COST

6

6 - Assembly

Set-up procedure of the modular subsystems:

1. Halves of the chassis are connected together using the modular plates.
2. Platform is connected on top of chassis.
3. Drive systems are connected to the chassis.
4. Linear actuators are mounted on the front and back end.
5. The manipulator is assembled on top of the platform.
6. Winch cable is connected to the hoist rings.

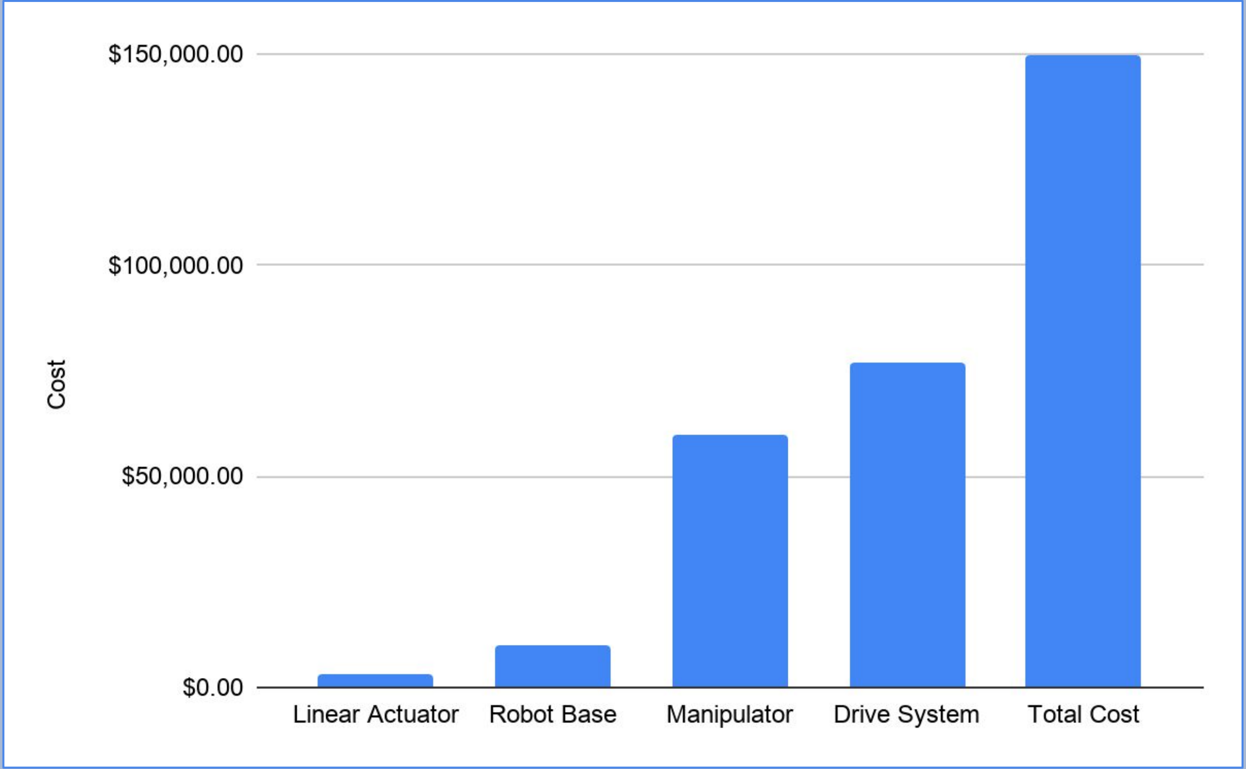


6 - Assembly

- Assuming 1 minute for each bolted connection
- Transition time of 30s between connections, the estimated set-up time for the assembly is 1.5 hours
- Connection of winch cables and electronics is not included in the time estimation

Task	*Number of connections (bolt + nut)*	*Total time estimate (s)*
Assemble modular halves of chassis	6 on bottom	510
Connect platform to chassis	14 = 6 modular plate + 4 connections to chassis	1230
Connect drive system to chassis	12 = 3 connections x 4	1080
Assemble manipulator on top of platform	4	420
Mount linear actuators	8 = 4x2	690
Total	44	3930
Total estimated time for assembly inside vessel	1 hr	

6 - Cost



$150,000.00
$100,000.00
$50,000.00
$0.00
Cost
Linear Actuator
Robot Base
Manipulator
Drive System
Total Cost

CONCLUSION

7

7 - Design Compliance

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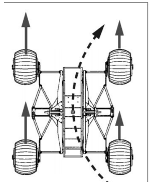
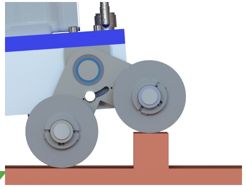


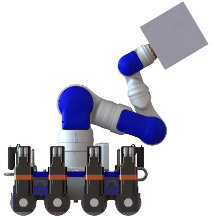
✓ Maneuverability

The robot must be able to travel along horizontal and vertical surfaces.



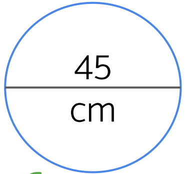
✓ Obstacles

The robot must overcome 3” x 3” ribs that span the circumference of the vessel.



✓ Payload

The manipulator arm must be able to support a 20 kg payload.



✓ Size

Each module must be able to fit within a 45 cm diameter hole.

✓ Rigidity

The robot must become rigid when performing inspections/repairs.

7 - Sustainability

AISI Steel is used for the manufacturing of the chassis, shafts, top plate, gearhead cover, and pivot system.

Steel is 100% recyclable, and can be recycled into the same material of the same quality again and again.

The modular design of the robot enables parts to be easily disassembled and reused or recycled, at the end of its lifecycle.

“The American steel industry is the cleanest and most energy-efficient of the leading steel industries in the world. Of the seven largest steel producing countries, the U.S. has the lowest CO_2 emissions per ton of steel produced and the lowest energy intensity”

7 - FUTURE WORK

Control system to regulate motor output

Optimize of the drive system to reduce number of motors

Optimize geometry and mass

$$a = \frac{\Delta v}{\Delta t}$$

Further kinematic analysis

Installation of electronics

Prototyping and testing

THANKS

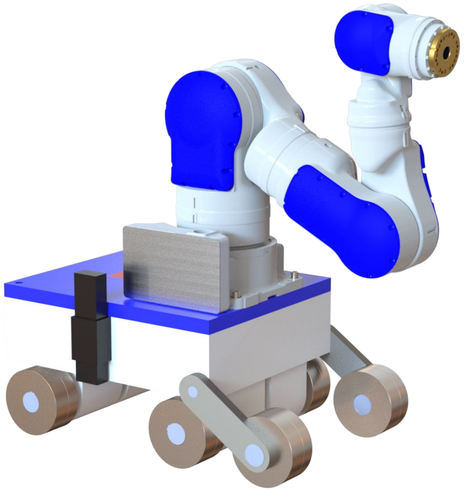
Course advisor: Dr. Tetsu Nakashima

Faculty advisor: Dr. Hossein Rouhani

Client: Dr. Tonya Wolfe,
Elementiam Materials and Manufacturing

Back-up Slides

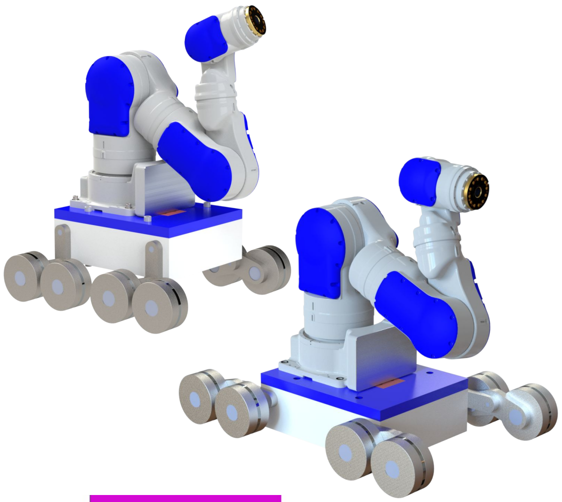
Concept 1 - High Clearance

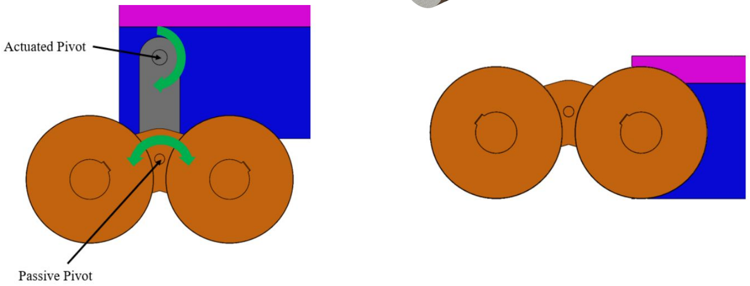


- ❑ Four driven wheels connected to wheel hub with base height clearance of 4 in.
- ❑ Two passive front wheels rigidly connected to chassis
- ❑ Skid steering through independent rotation of left and right wheels
- ❑ Linear actuators connected on left and right side of chassis
    - ❑ Equipped with permanent magnets at ends and actuated for additional rigidity during inspection/repair tasks

Design evaluation score: 193/255

Concept 2 - Pivot Platform

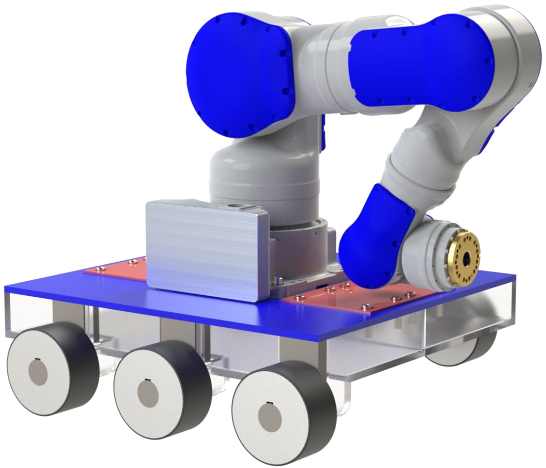




- Actuated pivoting wheel system enables platform to be raised and lowered
  - Raised position provides clearance overcoming obstacles
  - Lowered position provides lower COM for stability
- Bottom of chassis outfitted with permanent magnets
- Skid steering with hub motors connected to each wheel

Design evaluation score: 236/255

Concept 3 - Crawler



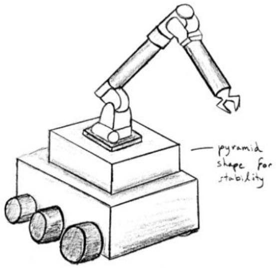
- Staggered wheels with independent suspension system on each wheel
- Suspension allows for constant contact with vessel surface through lockable gas springs on wheels
- Staggered wheels ensure loss of magnetic adhesion only one wheel at a time
- Wide wheel base distributes weight more evenly

Design evaluation score: 210/255

Additional Concepts

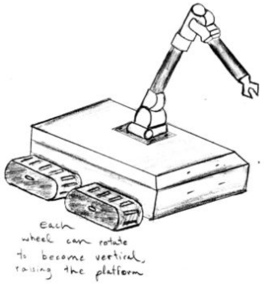
Conceptual Design 1

Go over ribs



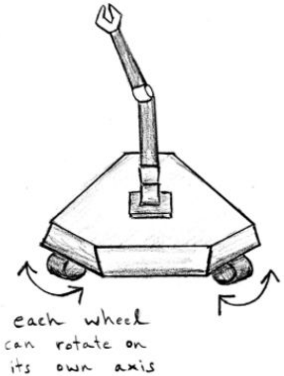
- Pyramid design
- Can't elevate platform
- Magnetic base
- Manipulator centered
- 6 wheels (magnetic)

Conceptual Design 2



- Box-shaped design
- Able to elevate platform
- Magnetic base
- Manipulator centered
- Ability to change tipping centre by adjusting the wheels

Conceptual Design 3 - The Roomba



- Triangular design
- Can't elevate platform
- Magnetic base
- Manipulator centered
- Each wheel is independent

Design Evaluation

OMIKRON ROBOTICS

Design Specification	High Clearance	Pivot Platform	Crawler
Traverse both vertical and horizontal surfaces while maintaining stability	Has 6 wheels of magnetic adhesion	Has 8 wheels of magnetic adhesion	Has 6 wheels of magnetic adhesion
Overcome 3in x 3in vessel ribs that span the circumference of the vessel	Utilizes 2 passive wheels to maintain magnetic contact point	Utilizes a passive rocking suspension to “rock” over ribs	Staggered wheels and passive suspension to crawl
Support a Manipulator arm with an end effector payload of 20 kg	Same platform	Same platform	Same platform
Modules Must fit through a 45 cm vessel opening	Bolted modular connections	Bolted modular connections	Bolted modular connections
Robot system must become rigid during inspection/repair tasks	Additional permanent magnetics to create additional adhesion	Platform is able to pivot the chassis to the ground and adhere with permanent magnets	Low COM distributed among 6 wheels with a lockable suspension

DESIGN Compliance

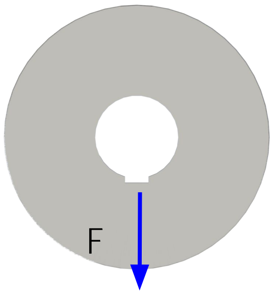
Design Specification	Technical Analysis for Compliance
Traverse both vertical and horizontal surfaces while maintaining stability	Static, dynamic, quasi-static analysis to avoid sliding, tipping, slipping and rolling of the robot. Skid steering analysis conducted
Overcome 3in x 3in vessel ribs that span the circumference of the vessel	Pivoting drive system with rotation limiting rod and spring system. Torque calculated for the selection of a motor and gearhead
Support a Manipulator arm with an end effector payload of 20 kg	Market analysis to scope a manipulator and Inertial forces of the arm calculated
Modules Must fit through a 45 cm vessel opening	All modules designed to fit through the opening
Robot system must become rigid during inspection/repair tasks	Linear actuators with permanent magnet as an emergency system. Drive system with 8 magnetic wheels lowering its centre of mass and providing a wider base

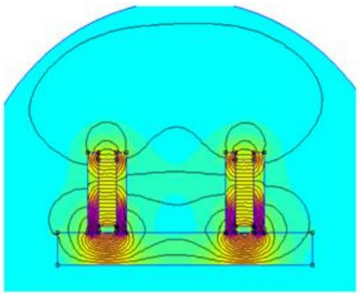
Magnetic Wheel

OMIKRON ROBOTICS

Magnetic Wheels

- 160 mm Diameter (~6 in)
- 1800 N Magnetic Force
- Polyurethane Rubber - increase friction





Magnetic force can be approximated as a concentrated force perpendicular to the surface

Skid Steering

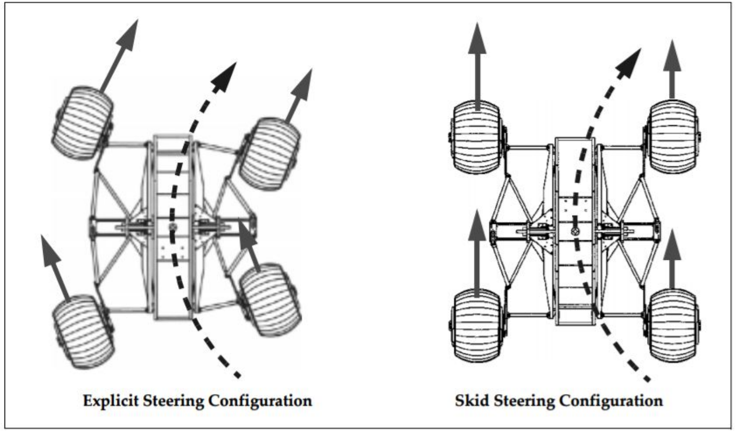
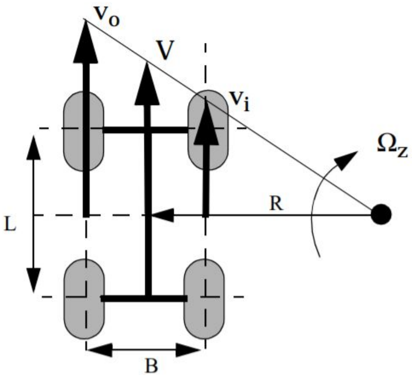
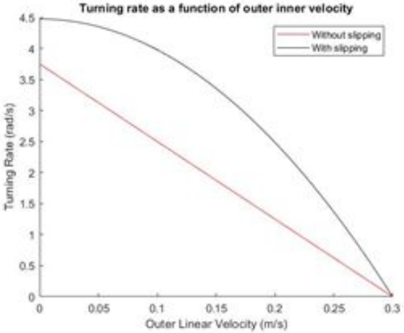


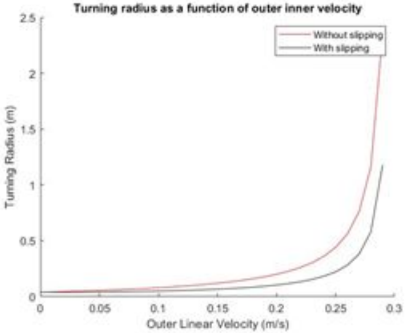
Figure 8: Explicit and Skid Turning Configurations



Variables:

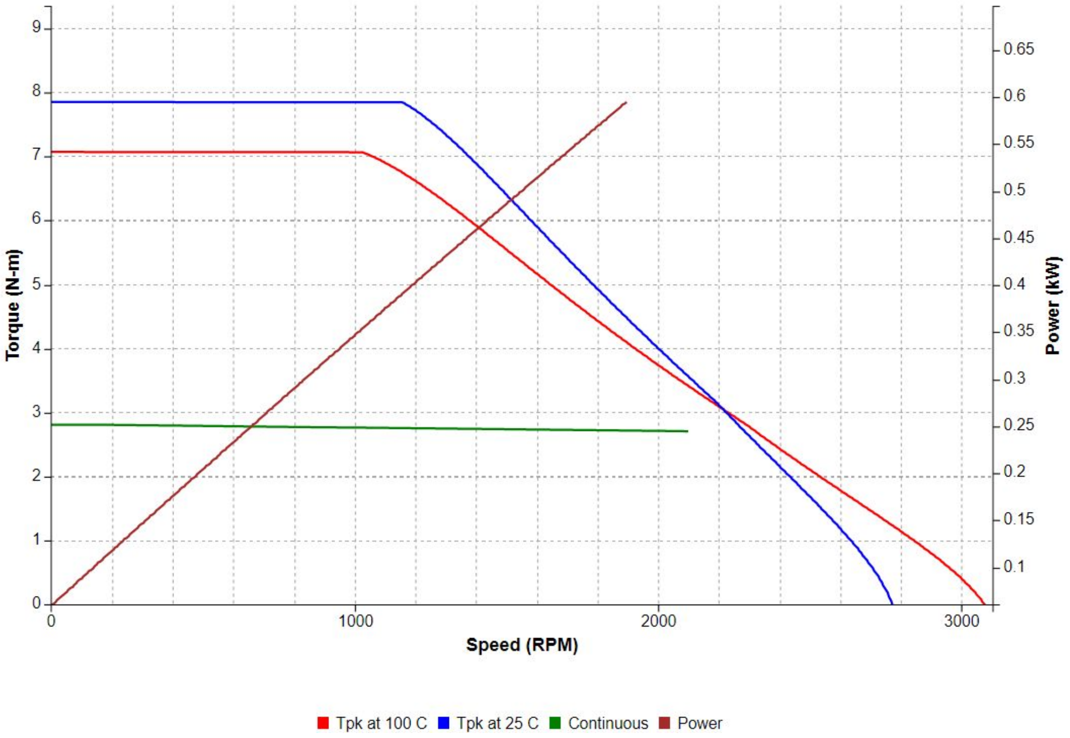
v_o = outside wheel velocity [m/s]
v_i = inside wheel velocity [m/s]
V = vehicle velocity [m/s]
Ω_z = vehicle angular velocity [rad/s]
R = vehicle turn radius [m]
L = vehicle length [m]
B = vehicle width [m]

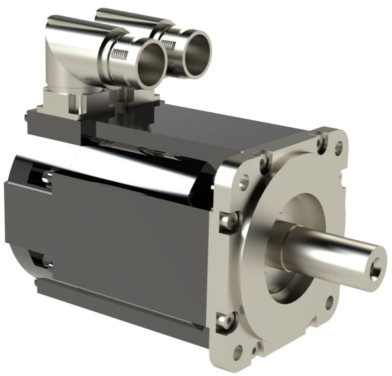




Motor Torque Chart

AKM2G-41D
Torque Chart



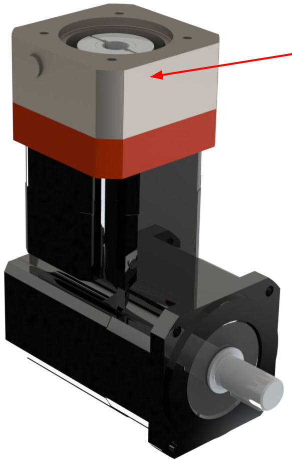


OMIKRON ROBOTICS

AkM2G-41D 240 V
Cont. Torque: 2.85 Nm
Peak Torque: 7.25 Nm
Length: 122 mm

Control System is required to regulate the output - Future work

Gear Head



DuraTrue 115-100 Right Angle

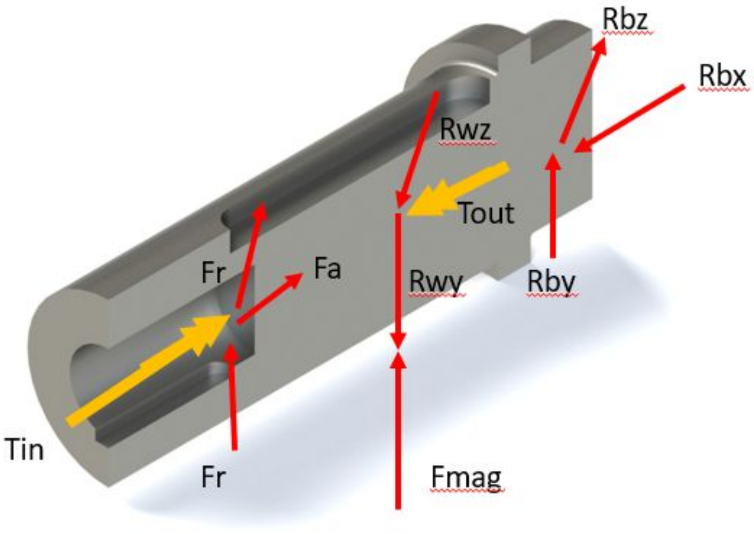
- DuraTrue 90-degree right angle planetary gear head
- 8 arc-min backlash
- Rated for 185 Nm continuous torque
- 100:1 Gear ratio

Component Analysis Summary

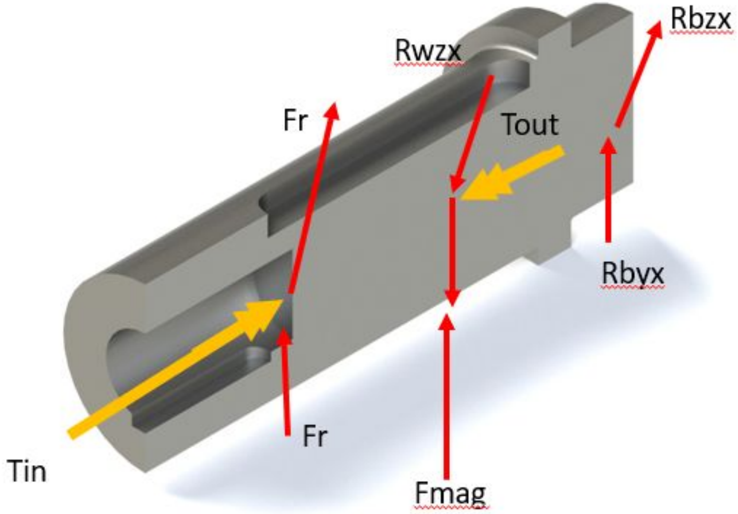
	TOP PLATE	WINCH CONNECTION	DRIVE SHAFT	FIXED SHAFT	GEAR HEAD HOUSING	V-SUPPORT
Factors of Safety	66	2.0	3.6	5.7	1.16	4.9

Shaft Analysis

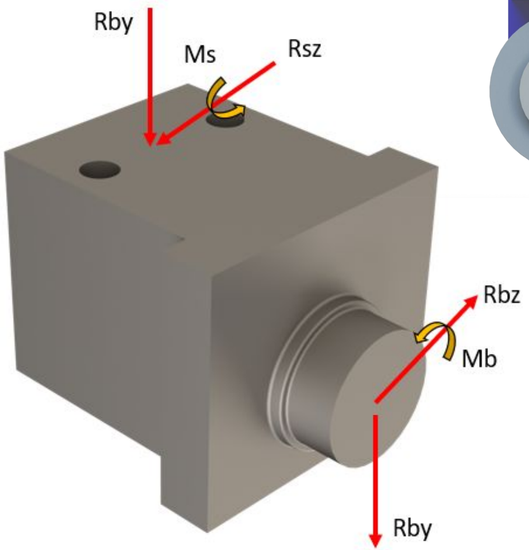
Conservative Vertical Case

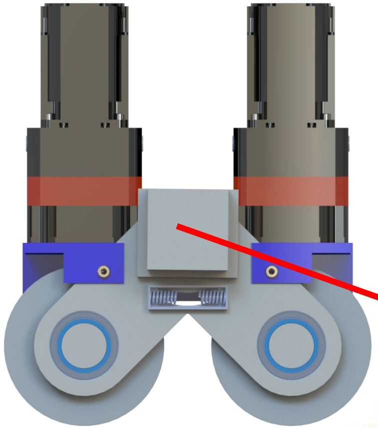


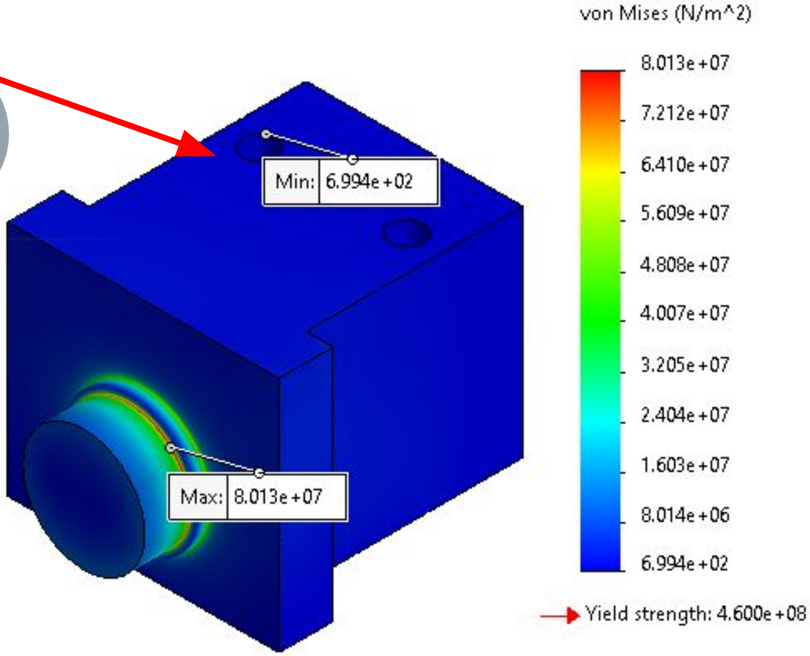
Conservative Horizontal Case



Fixed Shaft



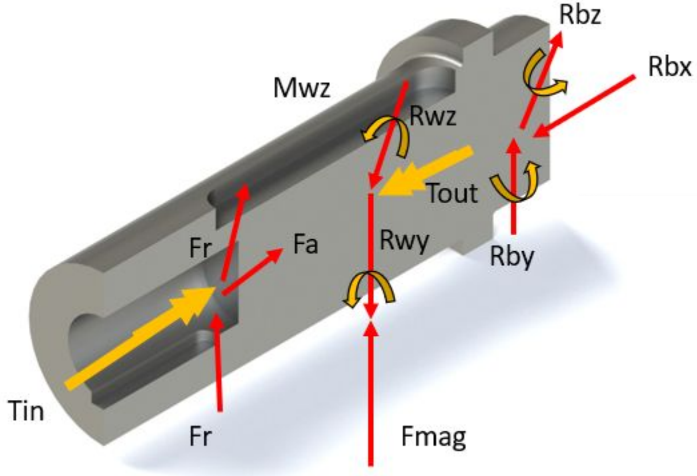


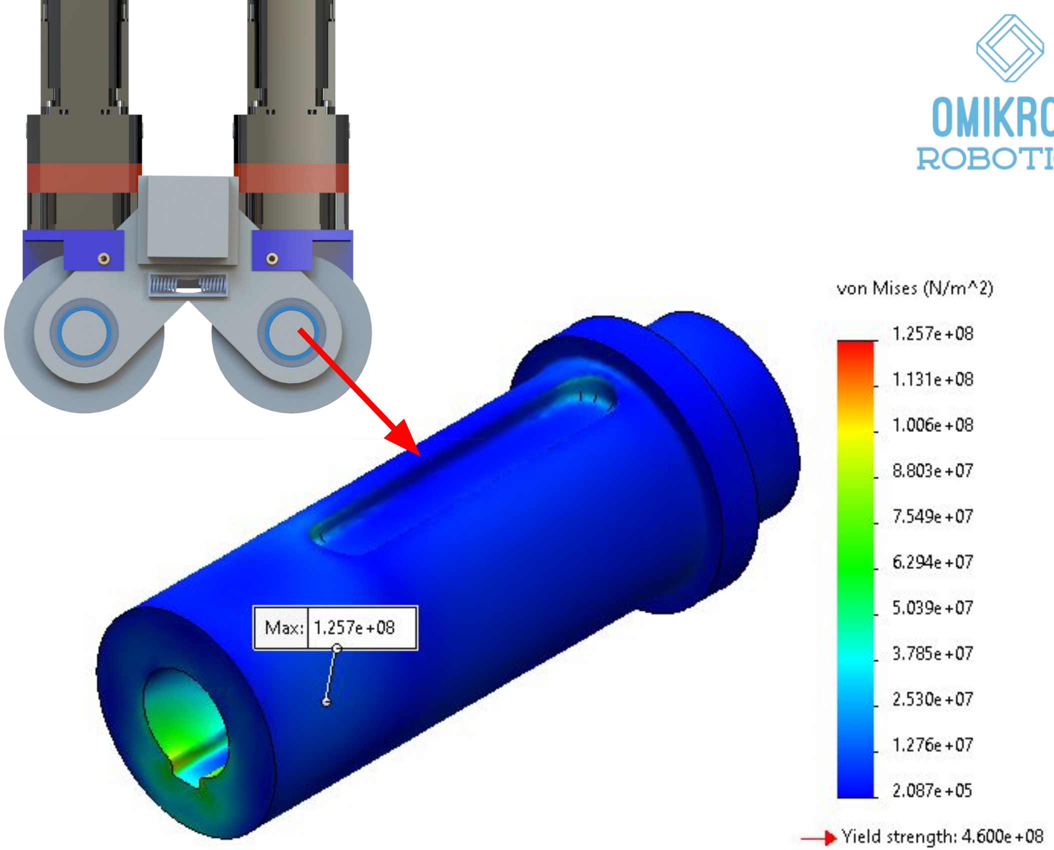


Conservative loading condition is the horizontal travel
Minimum Diameter : 41.38 mm

FOS: 5.7

Drive Shaft





Conservative shaft loading condition is the vertical wall travel
Minimum Diameter : 29.83 mm

FOS: 3.6

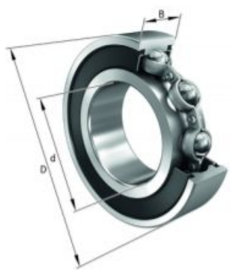
Analytic Shaft Summary

4130 Normalized Steel

$S_{ut} := 560\ \mathrm{MPa}$ $S_y := 460\ \mathrm{MPa}$

	Minimum Diameter (mm)	Analytic Safety Factor	Bearing Deflection (mm)	Motor Deflection (mm)	Wheel Deflection (mm)
Fixed Shaft	32.26	2.4	0.0004	-	-
Drive Shaft	29.8	6.6	0.0005	0.001	0.0006

Bearing Summary



FAG

S6009-2RSR-FD

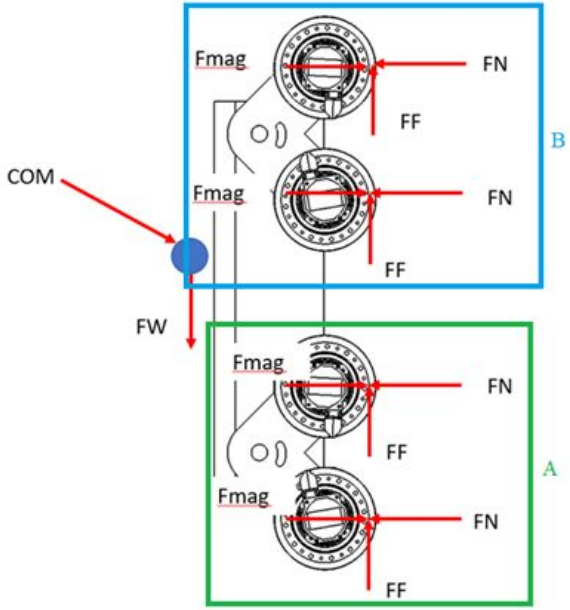
Deep groove ball bearing

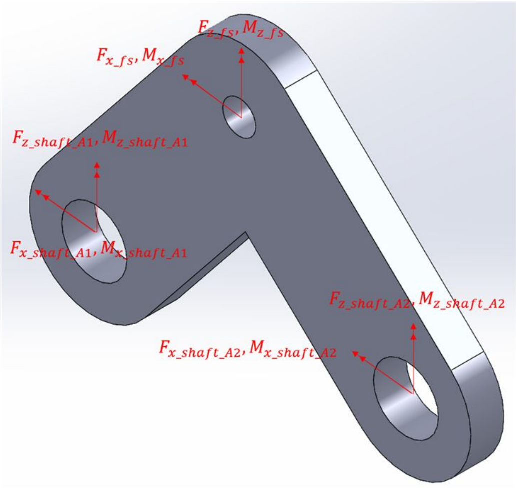
Schaeffler ID:
0947070490000

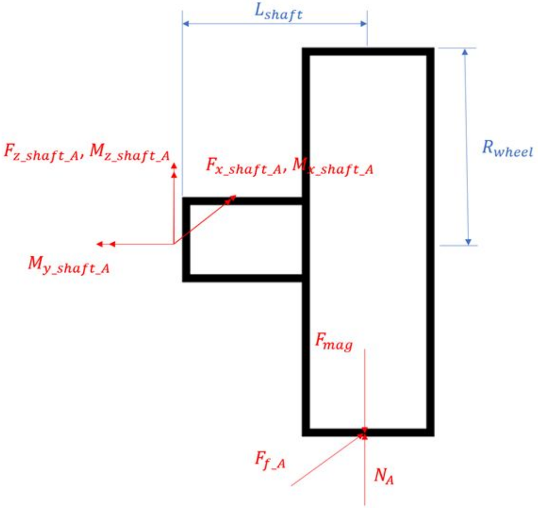
1 Year LCA	Bearing			Shaft		Deflection (mm)
	Bearing	Cr (N)	C0 (N)	Feff (N)	Cr (N)	
Fixed Shaft	26009-2RSR-FD	17800	12100	1557.9	185.2	4.00E-04
Drive Shaft	26009-2RSR-FD	17800	12100	1762.2	540.4	5.00E-04

52

Torque Summary







V-Support Calculations:

$$F_{x\_fs} := F_{x\_shaft\_A1} + F_{x\_shaft\_A2} = -1686.822\ \text{N}$$

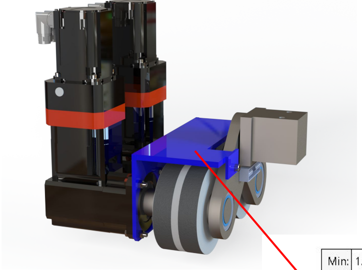
$$F_{z\_fs} := F_{z\_shaft\_A1} + F_{z\_shaft\_A2} = -1353.8297\ \text{N}$$

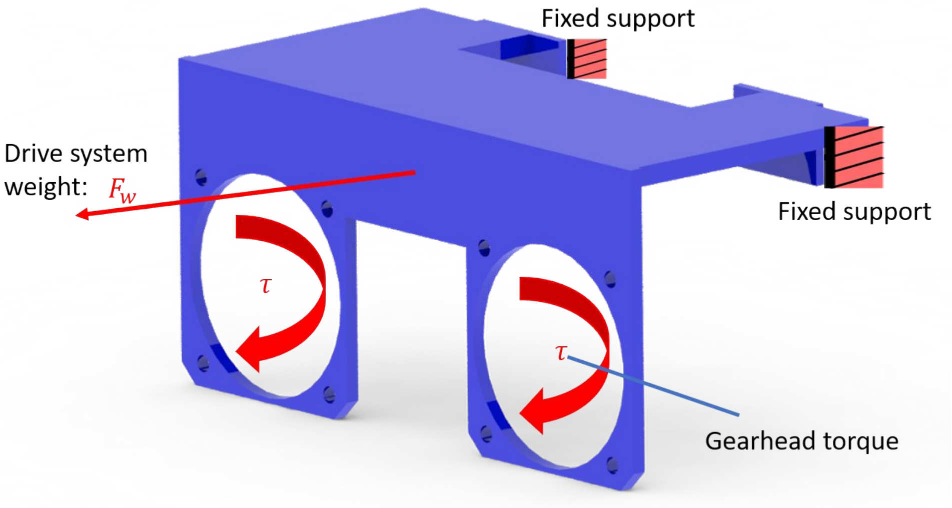
$$M_{x\_fs} := M_{x\_shaft\_A1} + M_{x\_shaft\_A2} = 81.2298\ \text{J}$$

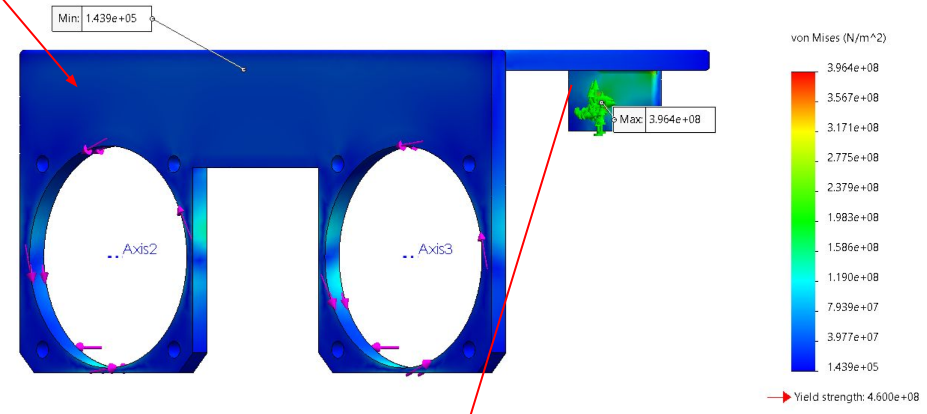
$$M_{z\_fs} := M_{z\_shaft\_A1} + M_{z\_shaft\_A2} = -101.2093\ \text{J}$$

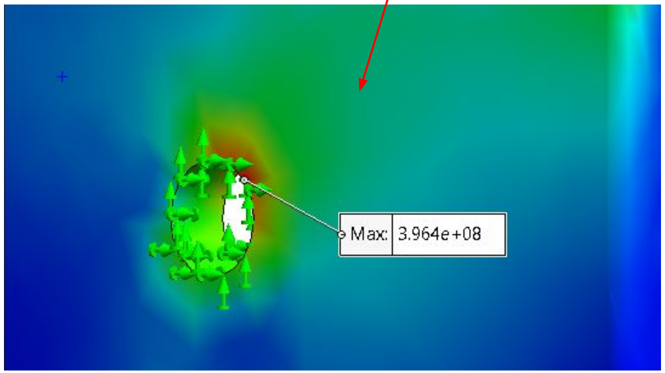
$$T_{brake} := \max\left(\left|\begin{bmatrix} M_{y\_shaft\_A1} \\ M_{y\_shaft\_A2} \end{bmatrix}\right|\right) = 96.3305\ \text{J}$$

Gearhead Housing





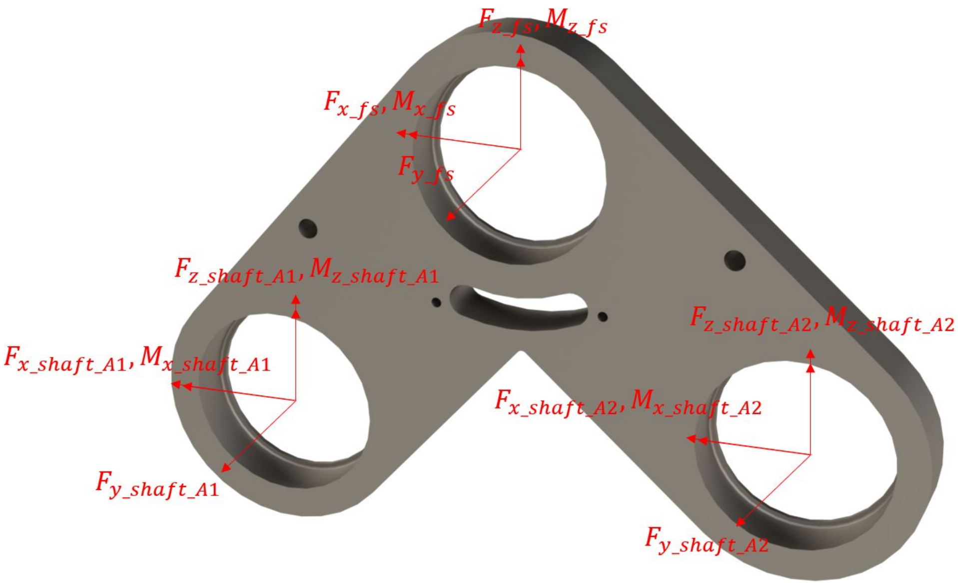




Assume conservative torque of 180 N.m applied by each gearhead, 15kg drive system weight.

FOS: **1.2**

V-support



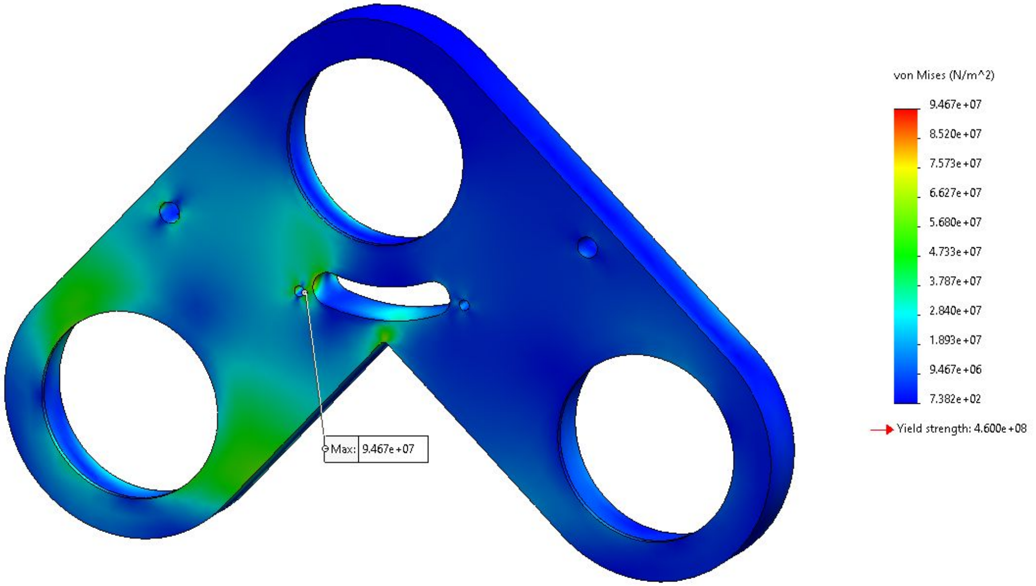
Buckling Analysis

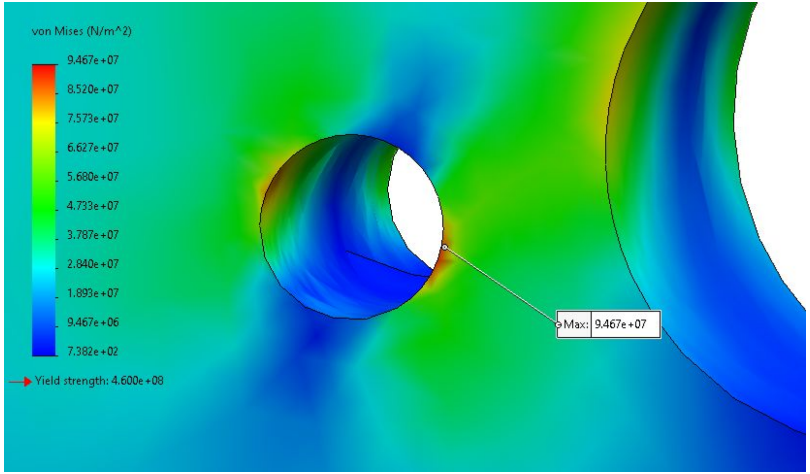
Actual Mass	500 kg
Maximum Mass	90,000 kg
Fails to Buckling?	No

Impact Analysis

Induced Stress	87 MPa
Yield Stress	460 MPa
Fails to Impact?	No

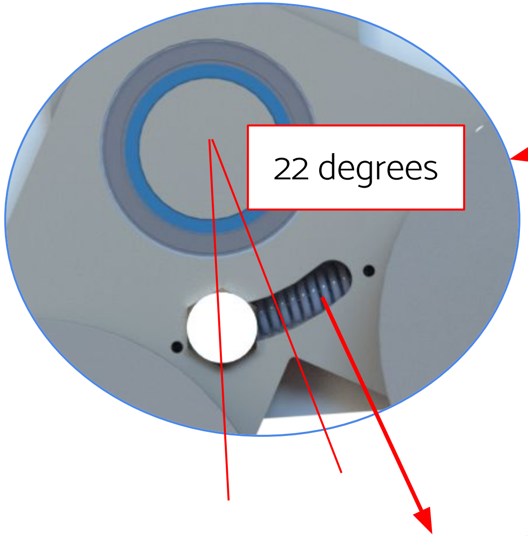
V-support

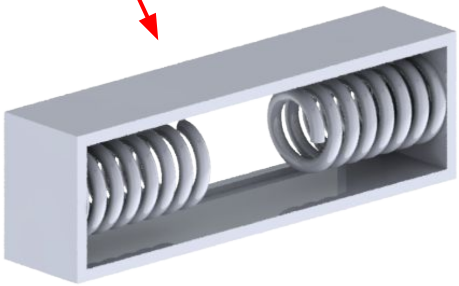


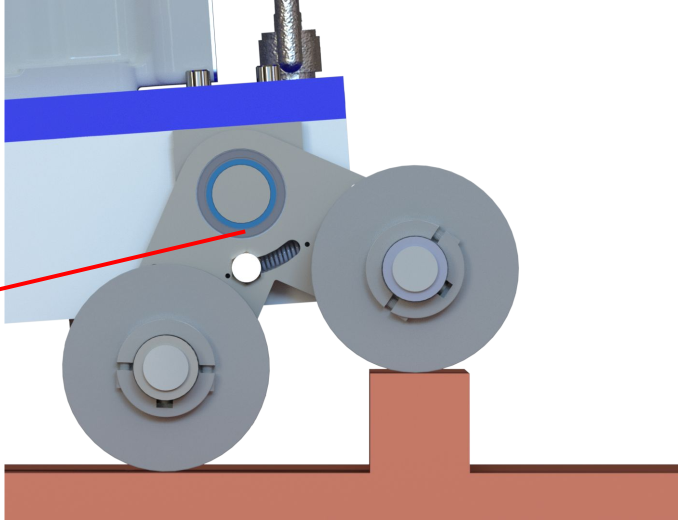


Conservative loading condition is the vertical wall travel
Minimum Diameter : 41.38 mm
FOS: 4.9

Linear Springs

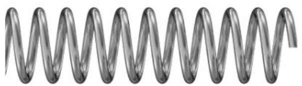






Corrosion-Resistant Compression Spring Stock

20" Long, 0.24" OD, 0.17" ID



$$\text{Rate of Cut Spring} = \frac{\text{Rate} \times \text{Lg.}}{\text{Cut Lg.}}$$

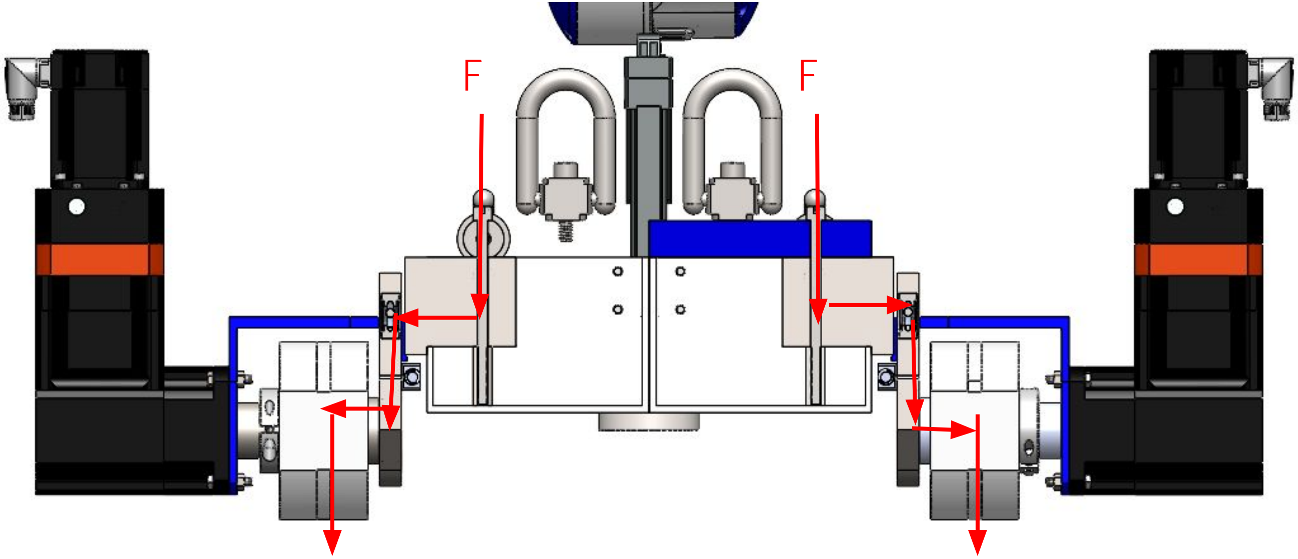
Two linear springs, always in compression
$6.40 each
Spring constant = 0.6 N/mm
Maximum deflection = 22 mm

Stability

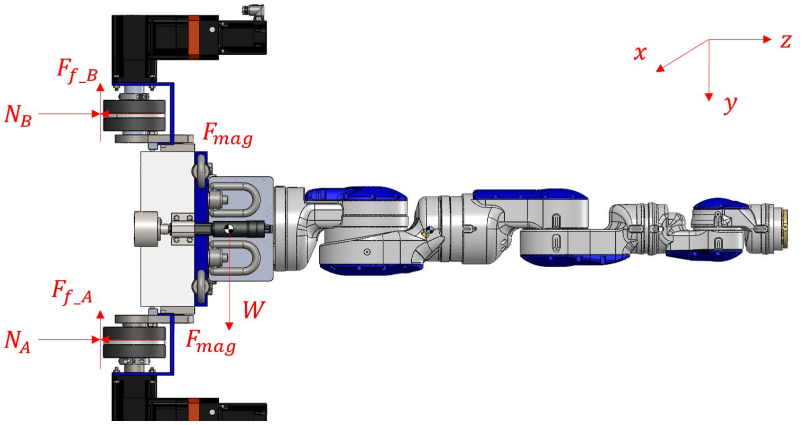
Free body diagram
Flowchart of the analysis

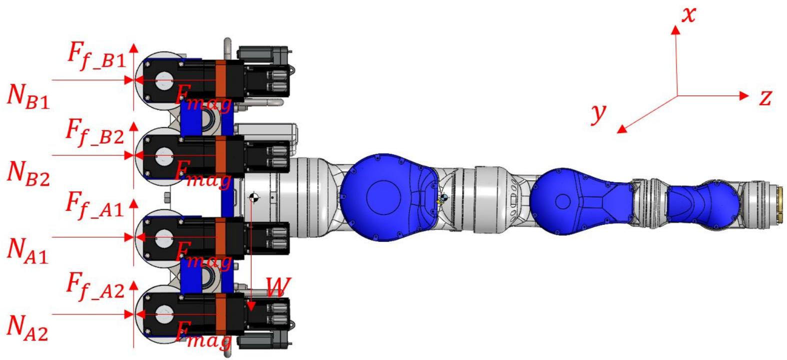
CASES STUDIED!
-horizontal
-Vertical
-Over obstacle (quasi-static)
-tipping, sliding (at all angles) , slipping, rolling, obstacles, in dynamics and static cases

Force Distribution



Stability Calculations





- FBDs were developed
- Equations of motions were used.
- The normal force at each wheel was solved for.
- Also solved for required torque at each wheel. Transmission was specified according to the largest torque requirement.
- Note that the vertical case on the wall is statically indeterminate in terms of friction. A conservative approximation was used.