CHIMP: CMU Highly Intelligent Mobile Platform

Eric Meyhofer
Modular Robotics
November 2014

National Robotics Engineering Center
Carnegie Mellon
THE ROBOTICS INSTITUTE

Carnegie Mellon University - NREC

Pittsburgh, Pennsylvania

Robotics Institute

- 500+ people
- $63M/year in revenue
- Research and Education

National Robotics Engineering Center

- 175+ people
- $31M/year in revenue
- Engineering and technology transfer

School of Computer Science

Topics

- Tartan Rescue Strategy
- CHIMP Mechanical Design
- Drive Joint Modules
- CHIMP Sensor Head

Tartan Rescue Strategy

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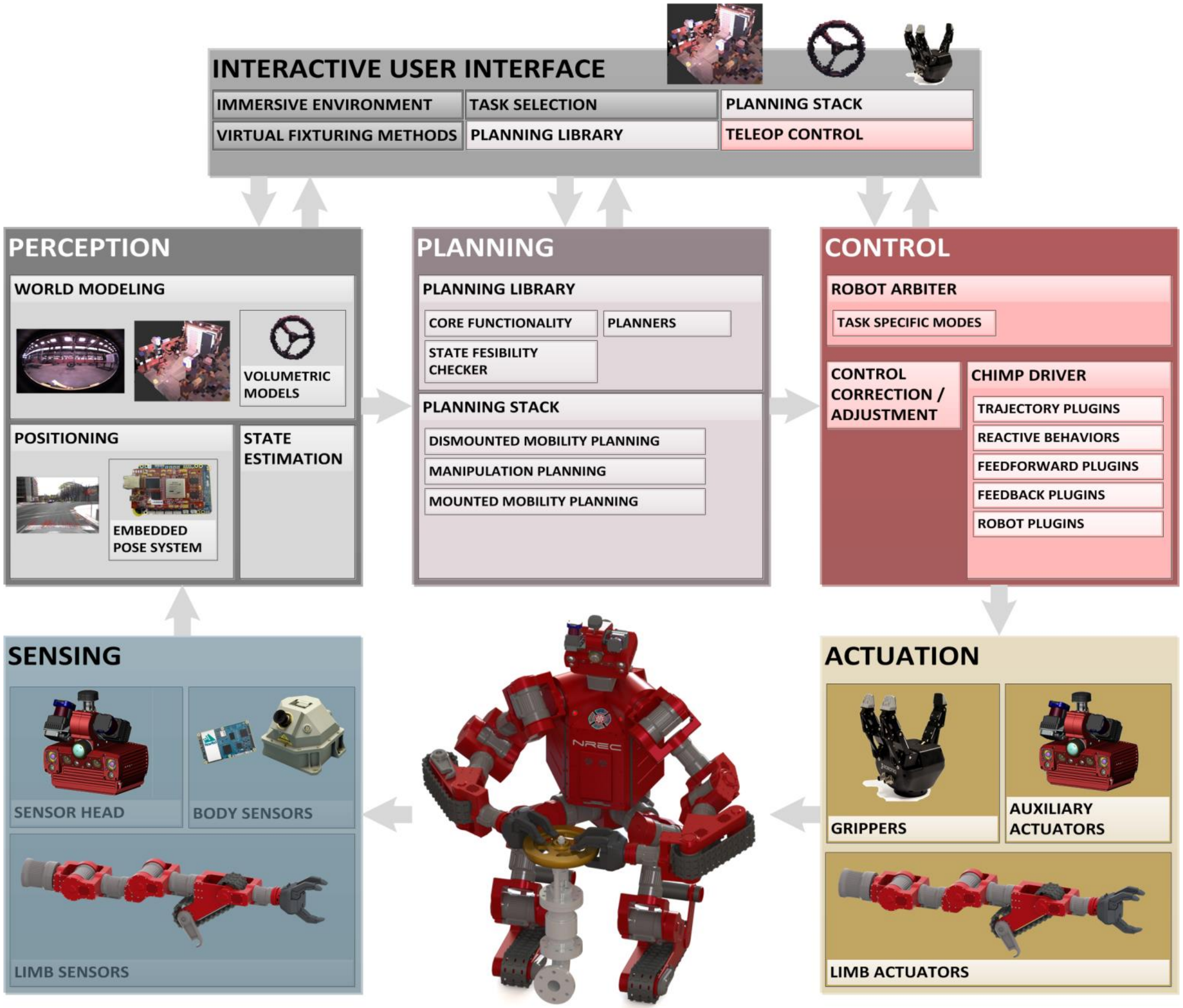
Aggressive Approach

- What is the optimal robotic platform for disaster response in human-engineered environments?
- NREC ambitiously designed and built CHIMP from scratch
- CHIMP is purpose-built for disaster response situations
- 12 months from concept to fabrication and assembly

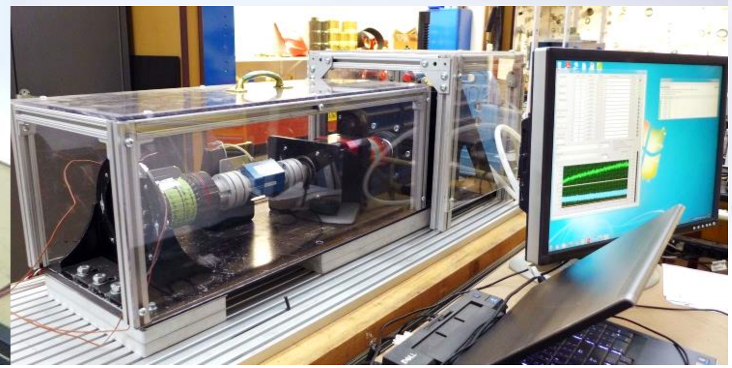
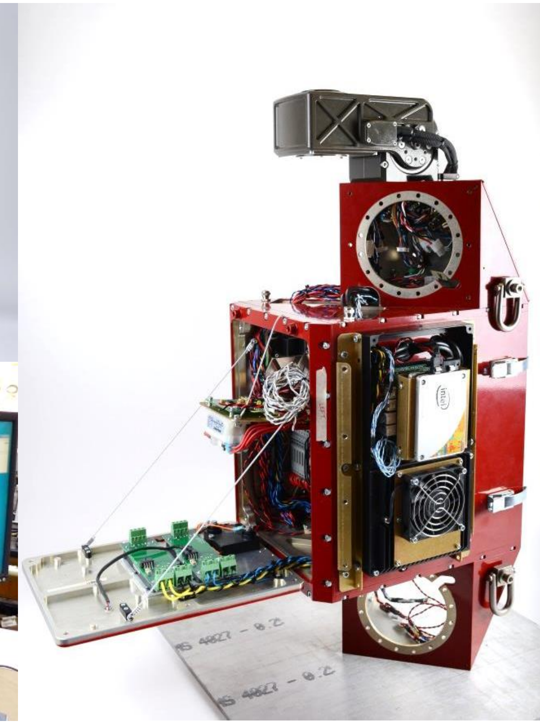
Our Approach

- **Statically Stable Robot**
  - Using 4-limb driving posture, our robot will be able to traverse uneven terrain without complex real-time full-body control
  - Modular approach for technology re-use and re-configuration
- **Tetherless Operation**
  - Wireless communications, estop, and battery power will eliminate the need for tether management
- **Superb Positioning and Perception**
  - NREC's proven positioning and perception technologies will allow the robot and remote operator to visualize and map the environment as it moves
- **Task Level Automation**
  - Blending the operator's intelligence and experience with the robot's mid-level autonomous behaviors will allow the robot to achieve tasks faster

System Overview



Development Strategy

Test components and sub-systems prior to integration to accelerate development and reduce risk

Work in parallel

Hardware Development

DARPA Robotics Challenge

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TARTAN RESCUE

PIs: Tony Stentz, Alonzo Kelly, Herman Herman, Eric Meyhofer

Systems Lead: David Stager

DARPA PM: Dr. Gill Pratt

CHIMP Mechanical Design

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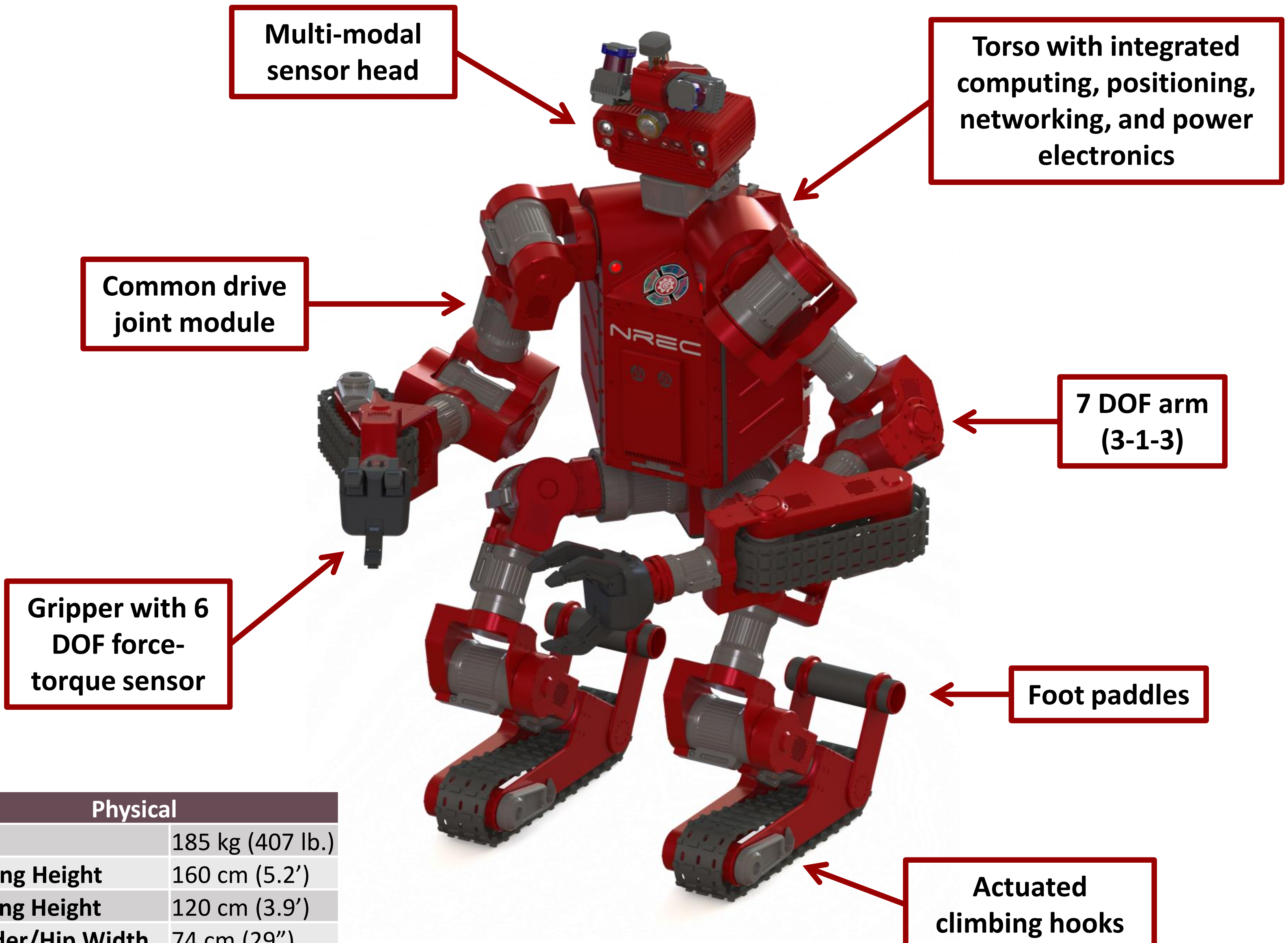
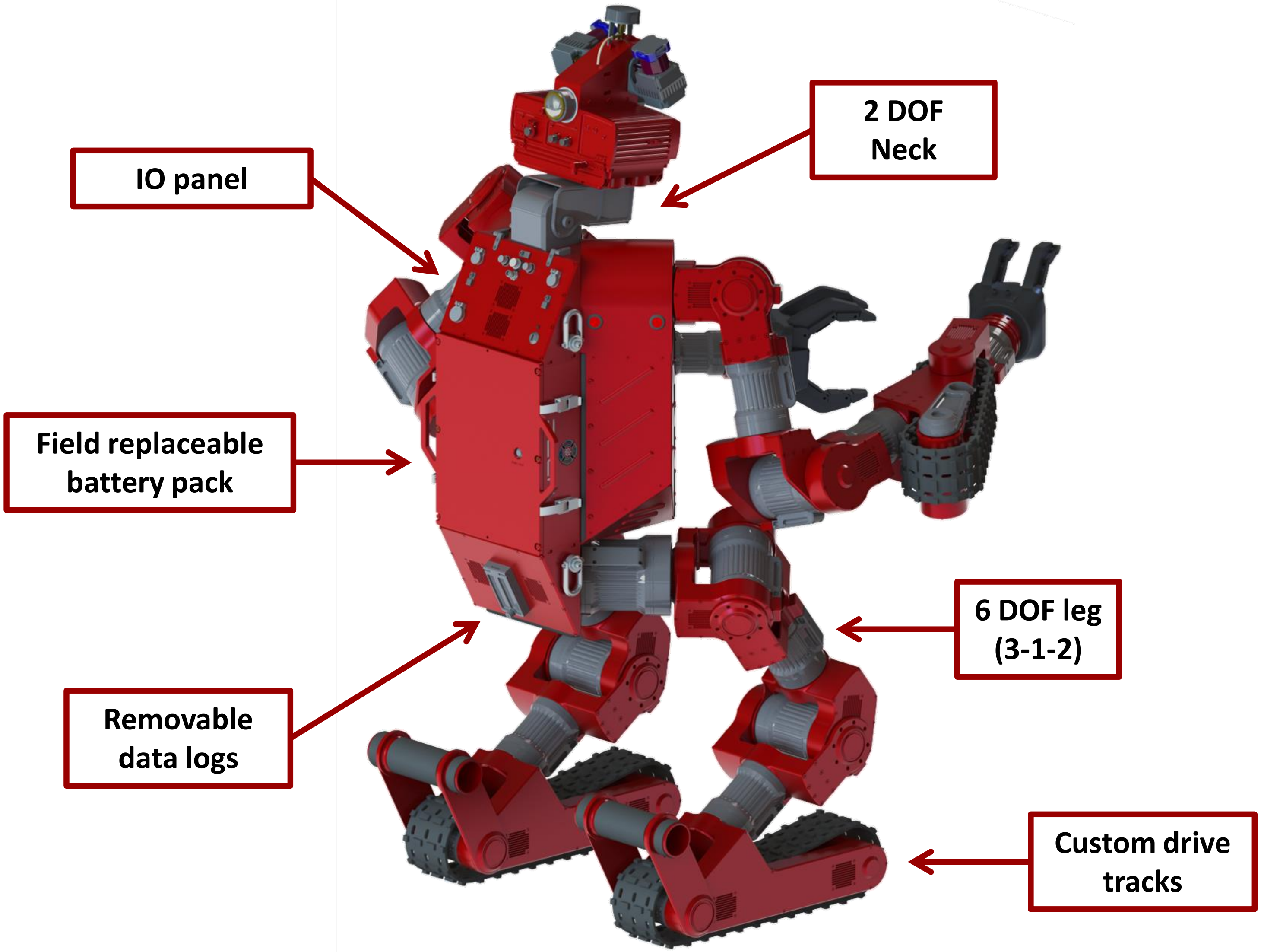
Mechanical Design Overview

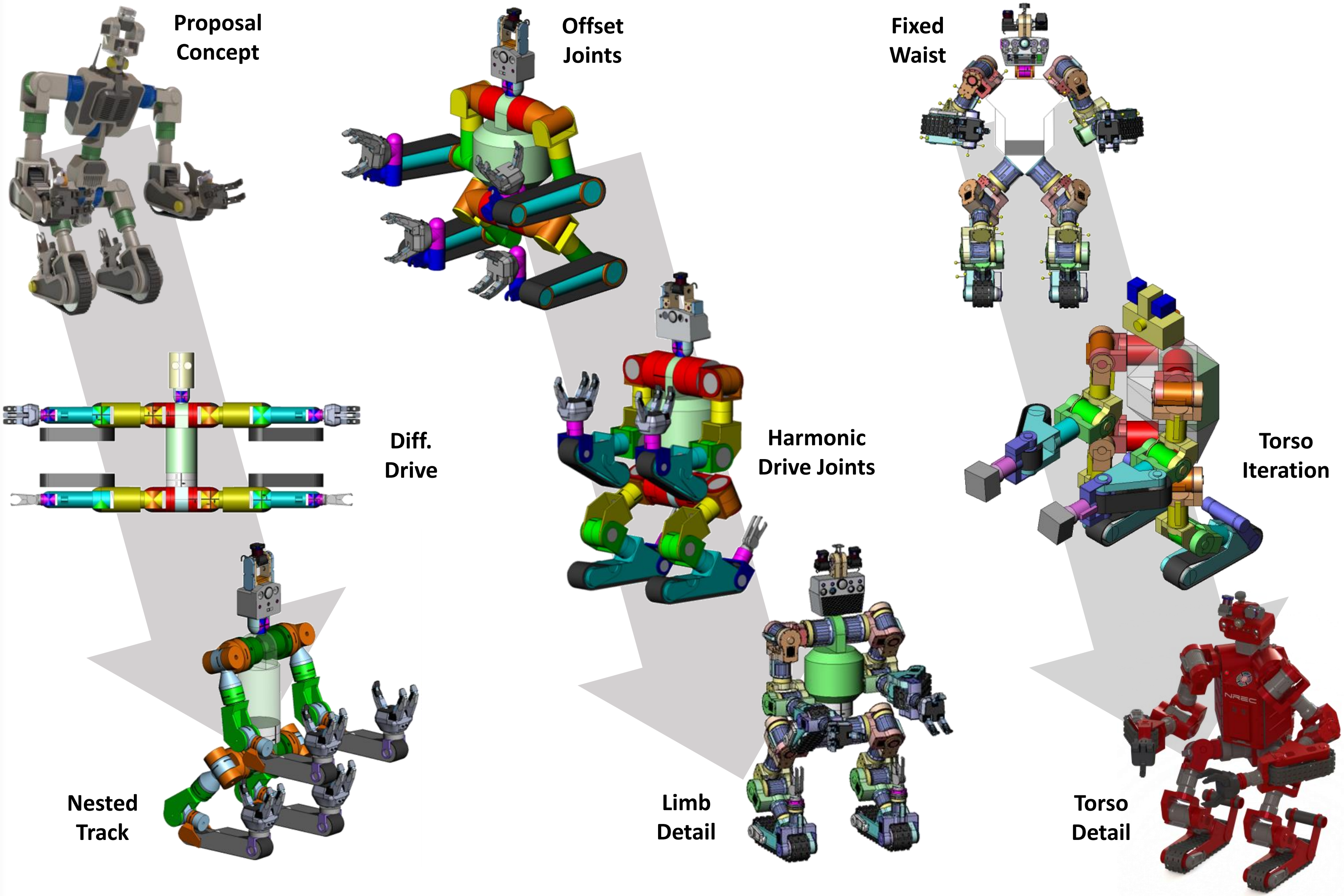


Physical	
Mass	185 kg (407 lb.)
Standing Height	160 cm (5.2’)
Crawling Height	120 cm (3.9’)
Shoulder/Hip Width	74 cm (29”)

Mechanical Design Overview



Mechanical Design Evolution



Tasks Completion

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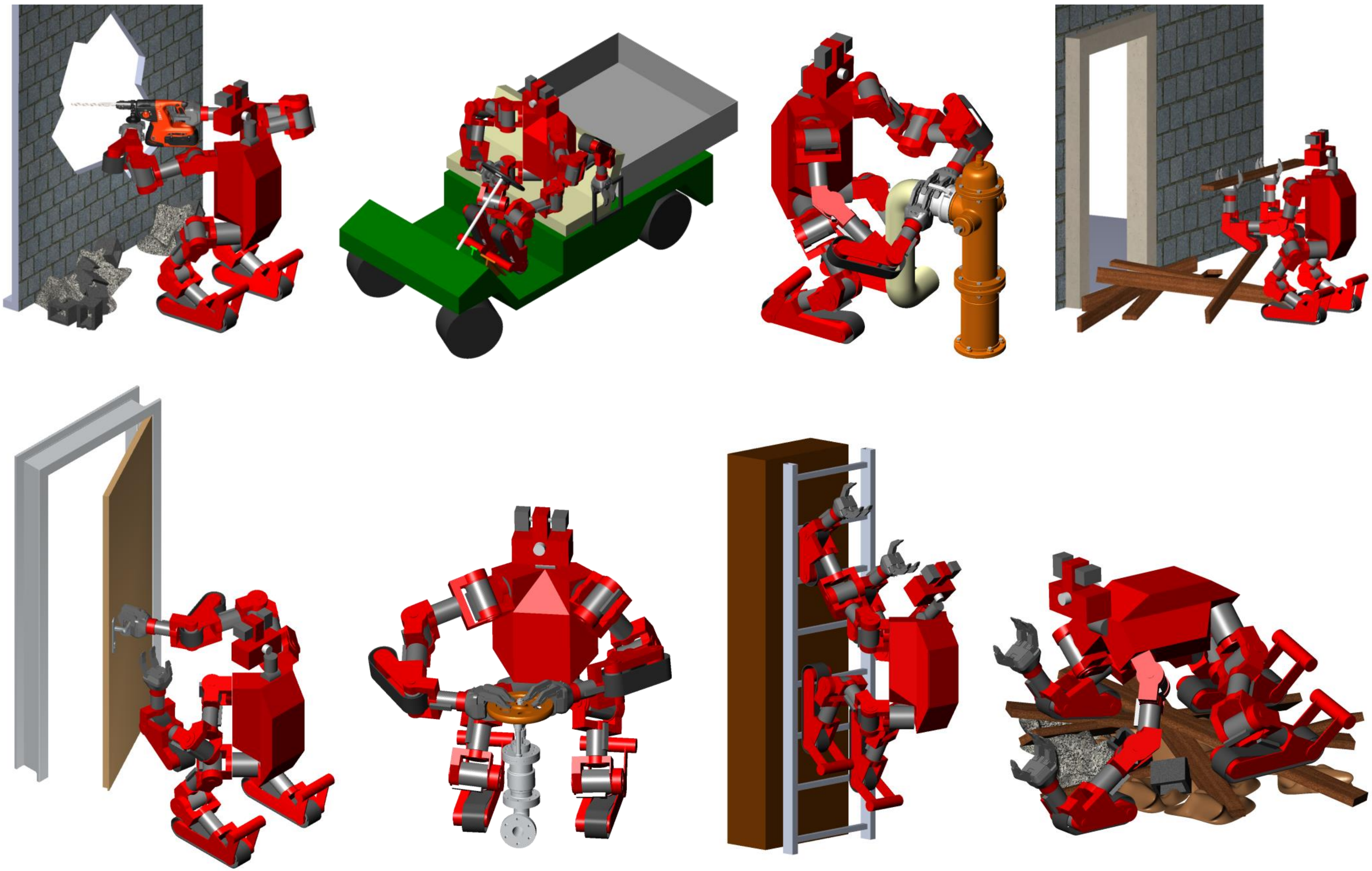

Final Mechanical Design

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Head Sensor	2 LIDAR (nodding)
	2 panamorphic cameras
	2 stereo camera pairs
	Illuminator
	GPS receiver
Limb Sensor	Stereo camera pair
	Illuminator

Configuration	
Degrees of Freedom	45 total: 14 in 2 arms (7 per) 12 in 2 legs (6 per) 2 neck (head twist & lift) 1 LIDAR (nodding) 8 in 2 grippers (4 per) 4 in 4 tracks (1 per) 4 in 4 hooks (1 per)
Joint Modules	4 sizes, clutched
Grippers	Robotiq 3-Finger Adaptive

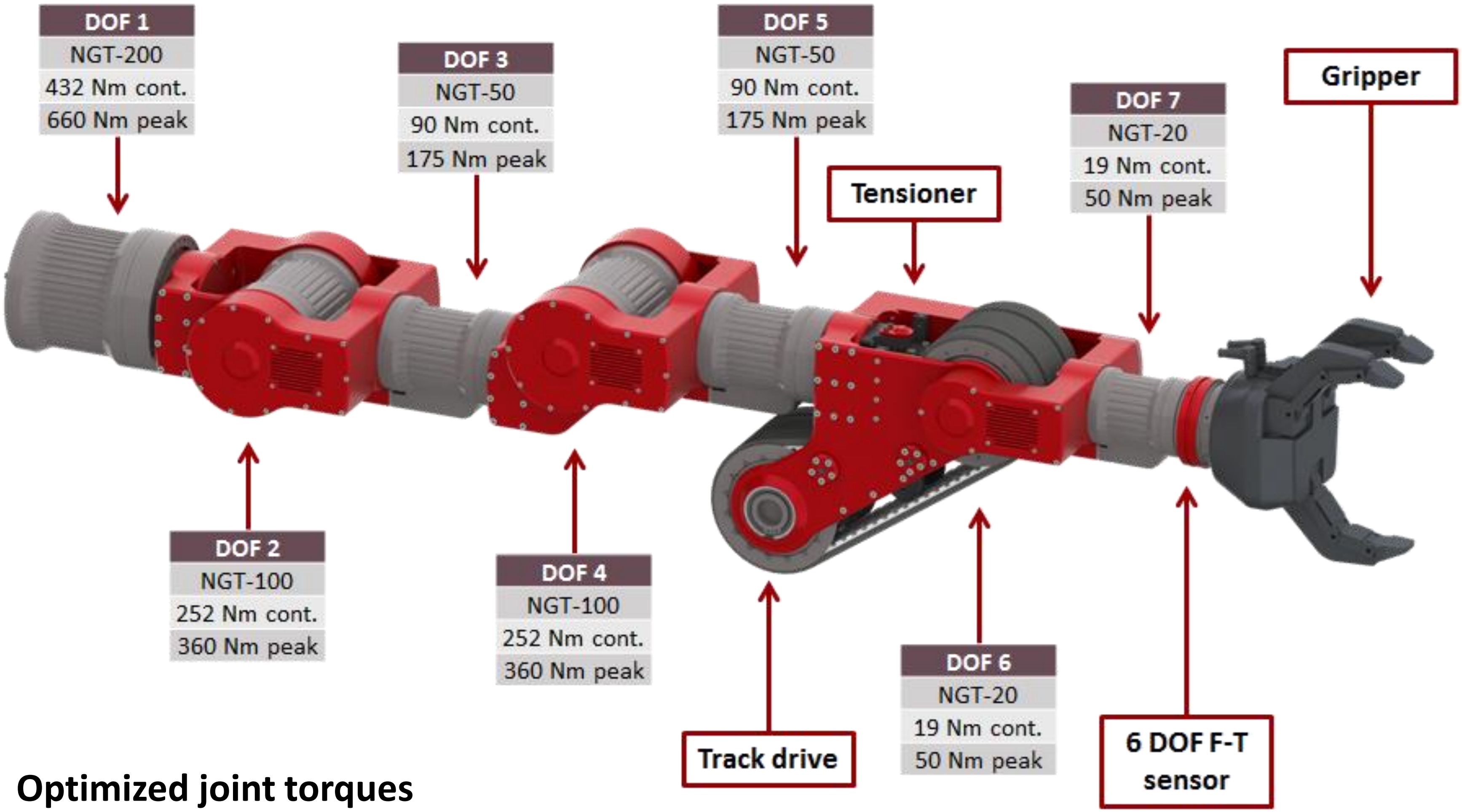
Electrical	
Bus Voltage	60 VDC
Batteries	BB-2590 Li-Ion (4P-2S)
Battery Energy	2.4 kWh
Shunt	NREC Custom
Charger	Off-board
APU	Off-board 600 Wh

Data/Signal/Control	
Control	RC, TeleOp, Autonomous
Encoders	18 bits absolute
Computing	Intel Core i7 3820QM (2 torso, 1 head)
Data	GigE, CAN
Communication	WiFi
Status	LED Indicators

Environmental	
Protection	IP 52 (dust protection; water drip)
Ambient Temp.	38 ^{o}C (100 ^{o}F)
Cooling	Forced air and natural convection

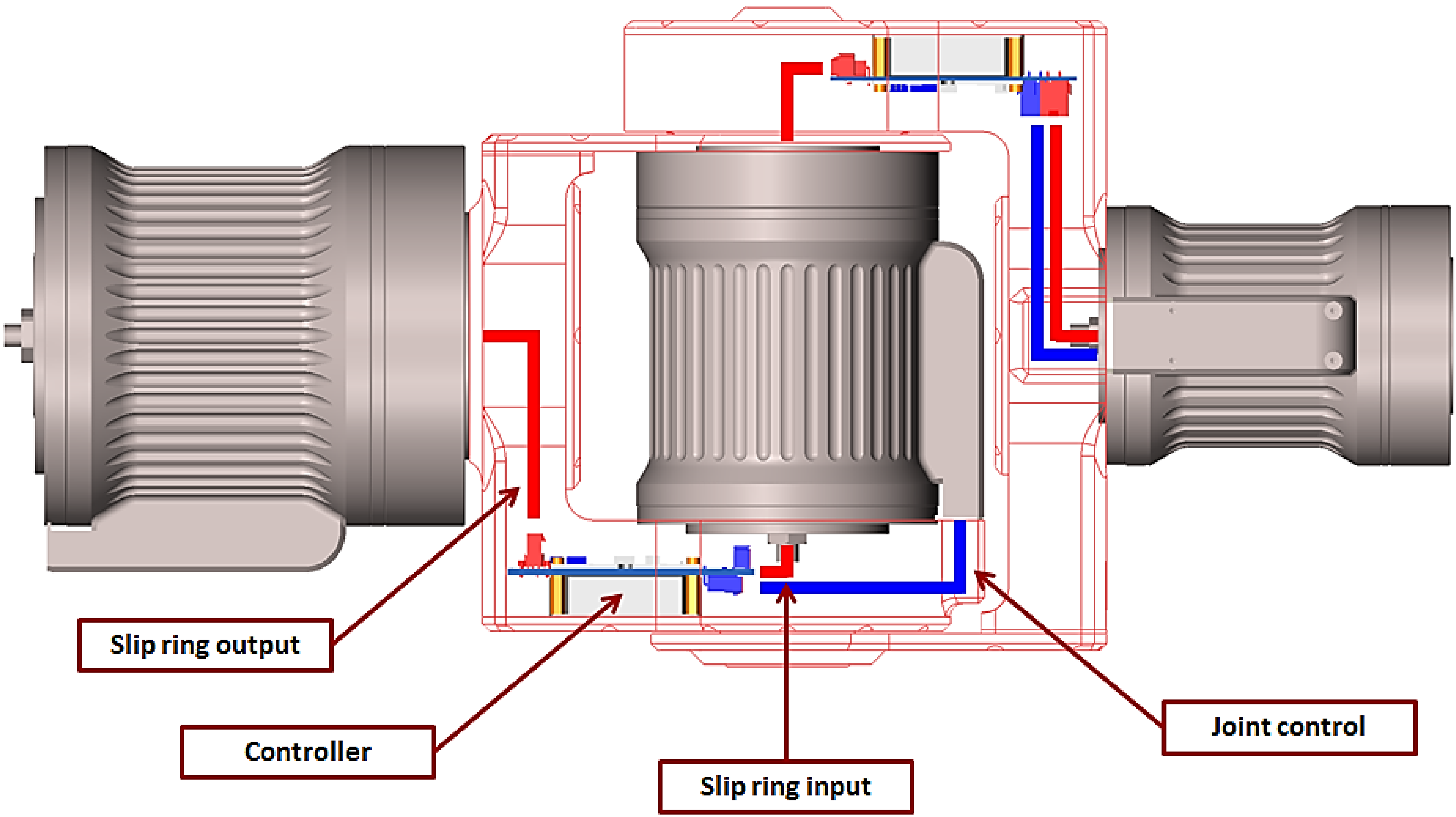
Physical	
Mass	185 kg
Standing Height	160 cm
Crawling Height	120 cm
Shoulder/Hip Width	74 cm

Limb Overview



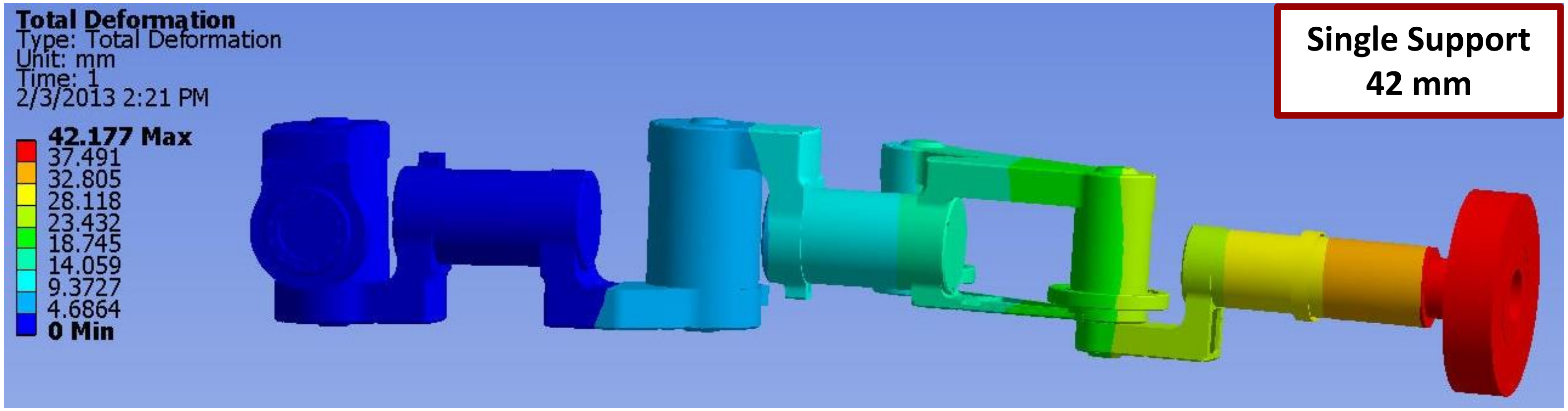
- **Optimized joint torques**
- **Optimized track workspace**
- **Configurable for arms and legs**
- **Mass: 35.7 kg; Reach: 1.1 m**

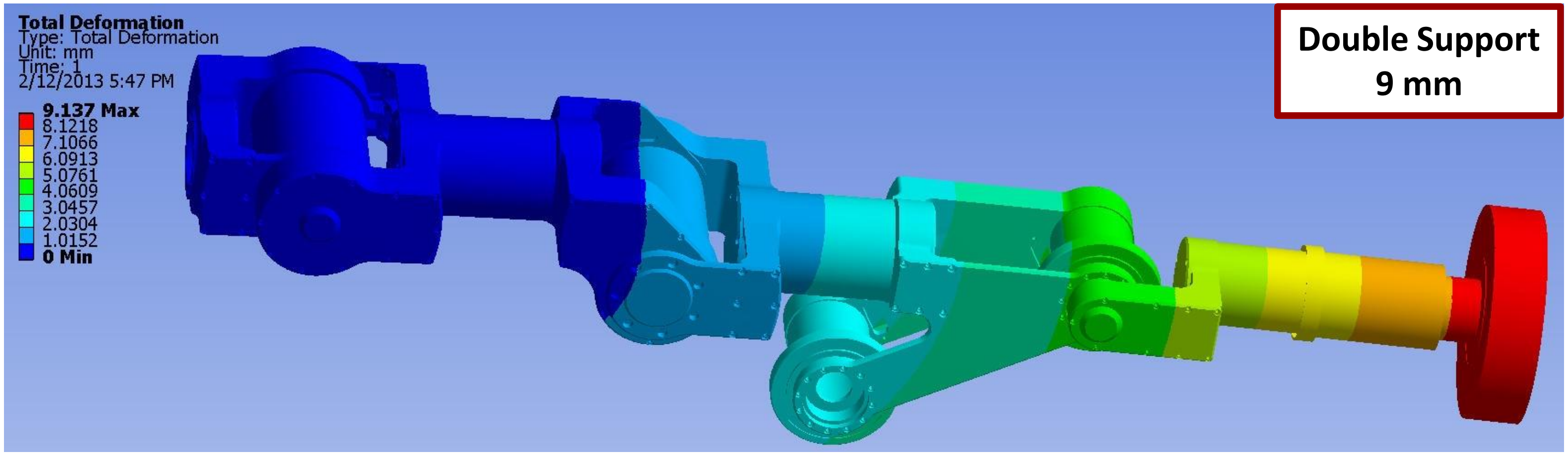
Limb Assembly



Limb Stiffness

DRC arm displacements under the arm weight and a payload of 5 kg

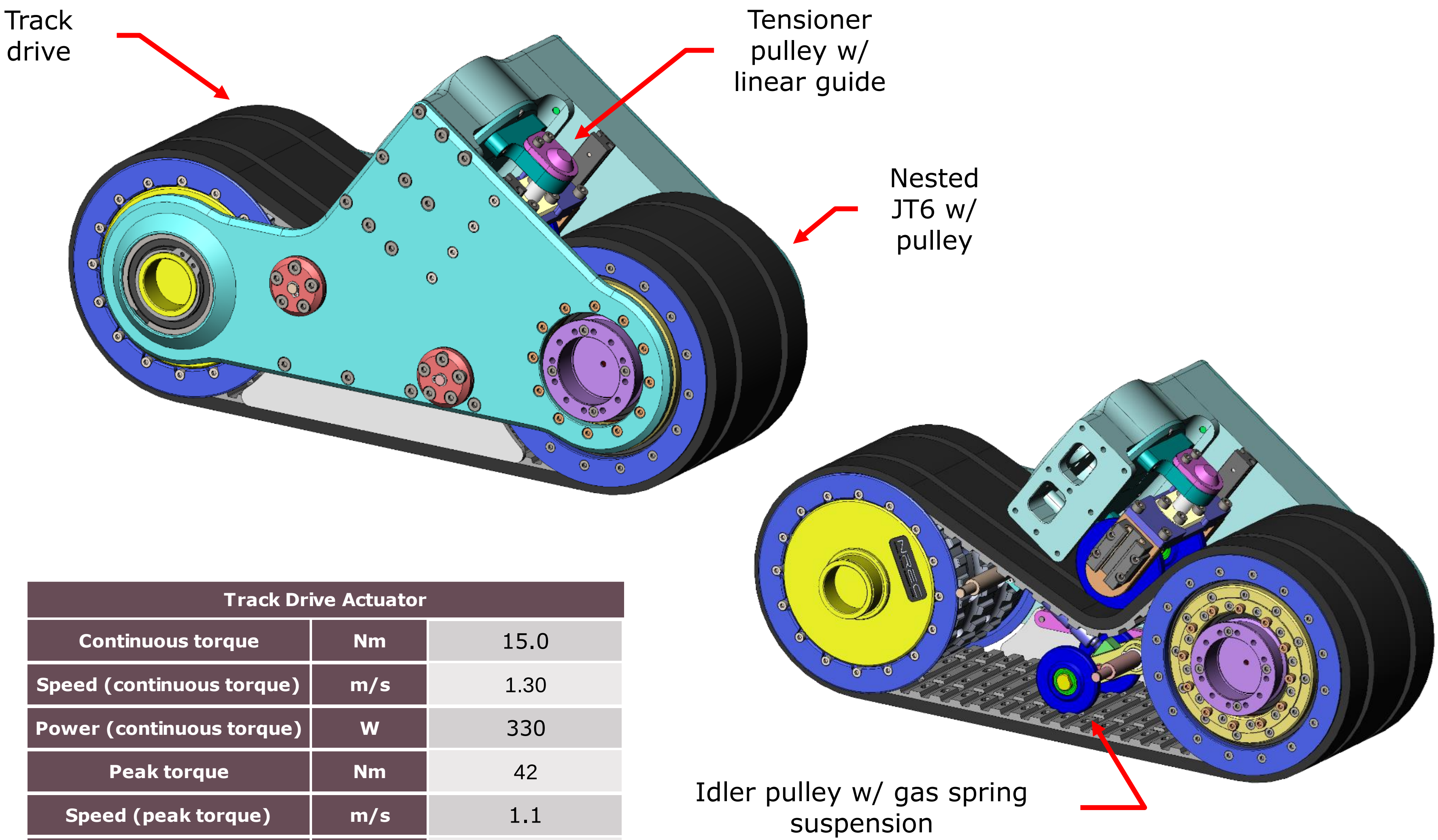




Gripper displacement with out of plane load (as shown): 9.14 mm
Gripper displacement with in plane load: 7.3 mm

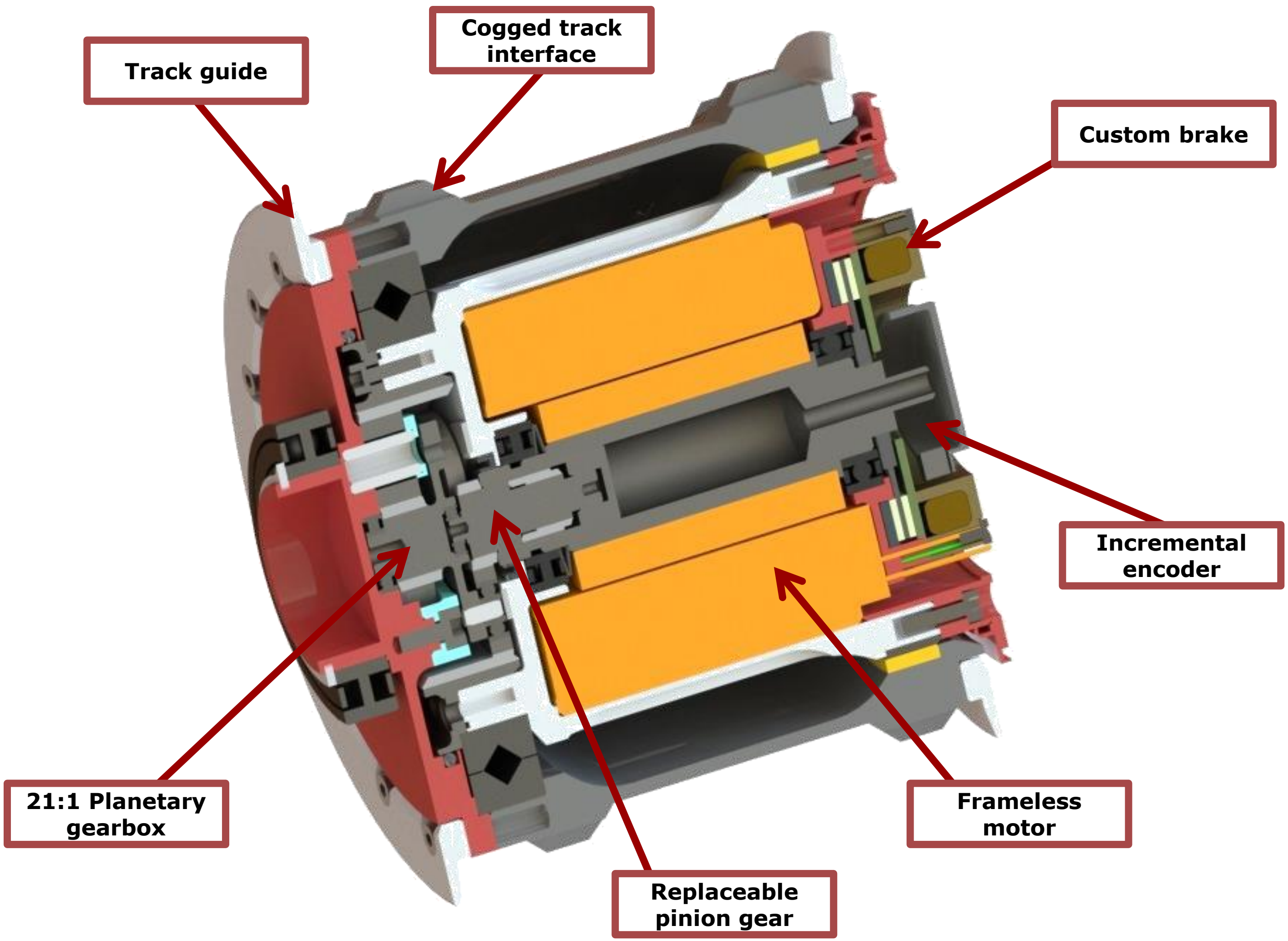
Double support meets 1 cm position accuracy requirement
Unmeasured deflection minimized (average of ~4 mm measured)

Track Overview



Track Drive Actuator		
Continuous torque	Nm	15.0
Speed (continuous torque)	m/s	1.30
Power (continuous torque)	W	330
Peak torque	Nm	42
Speed (peak torque)	m/s	1.1
Power (peak torque)	W	750

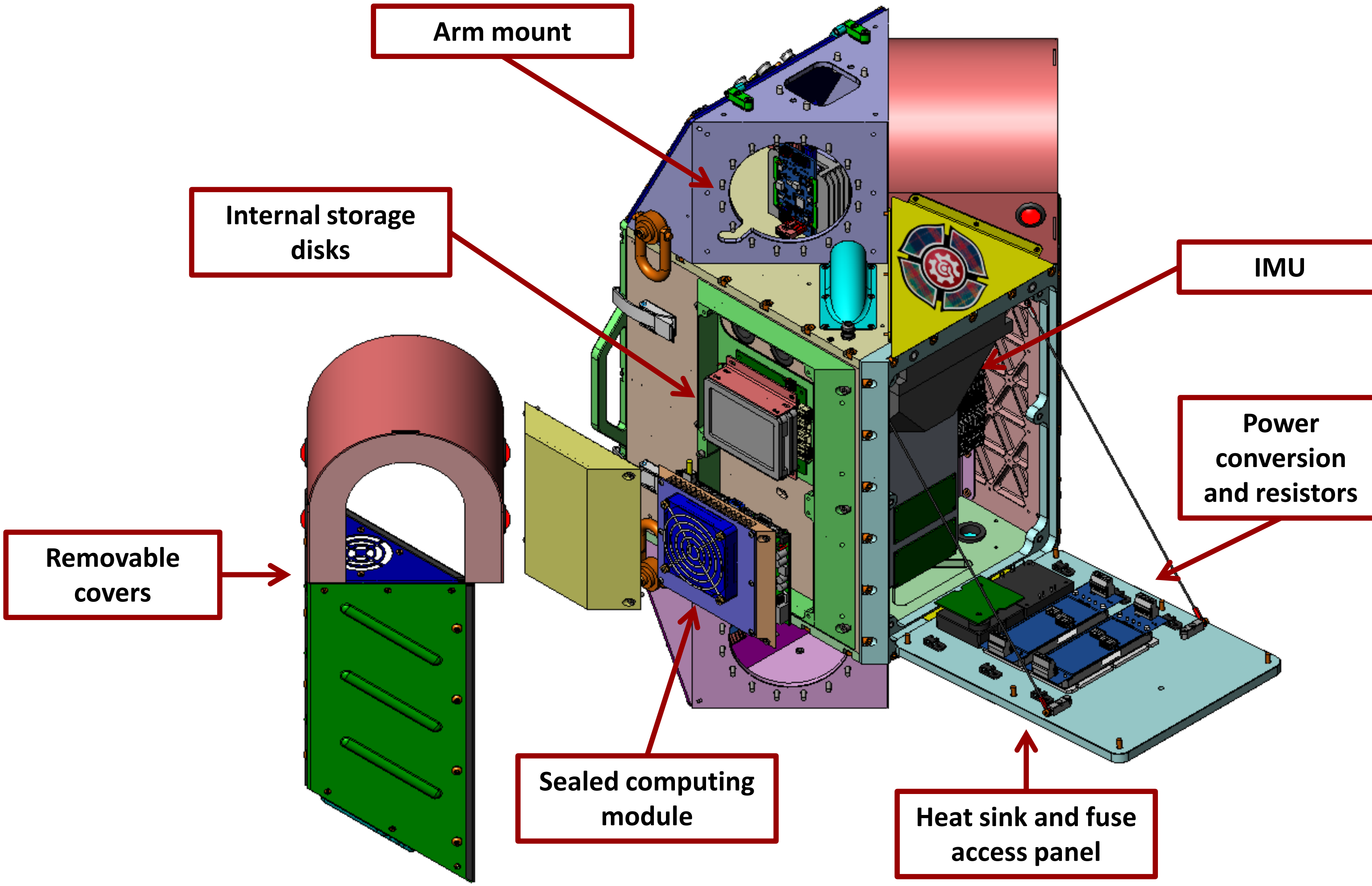
Track Drive Actuator



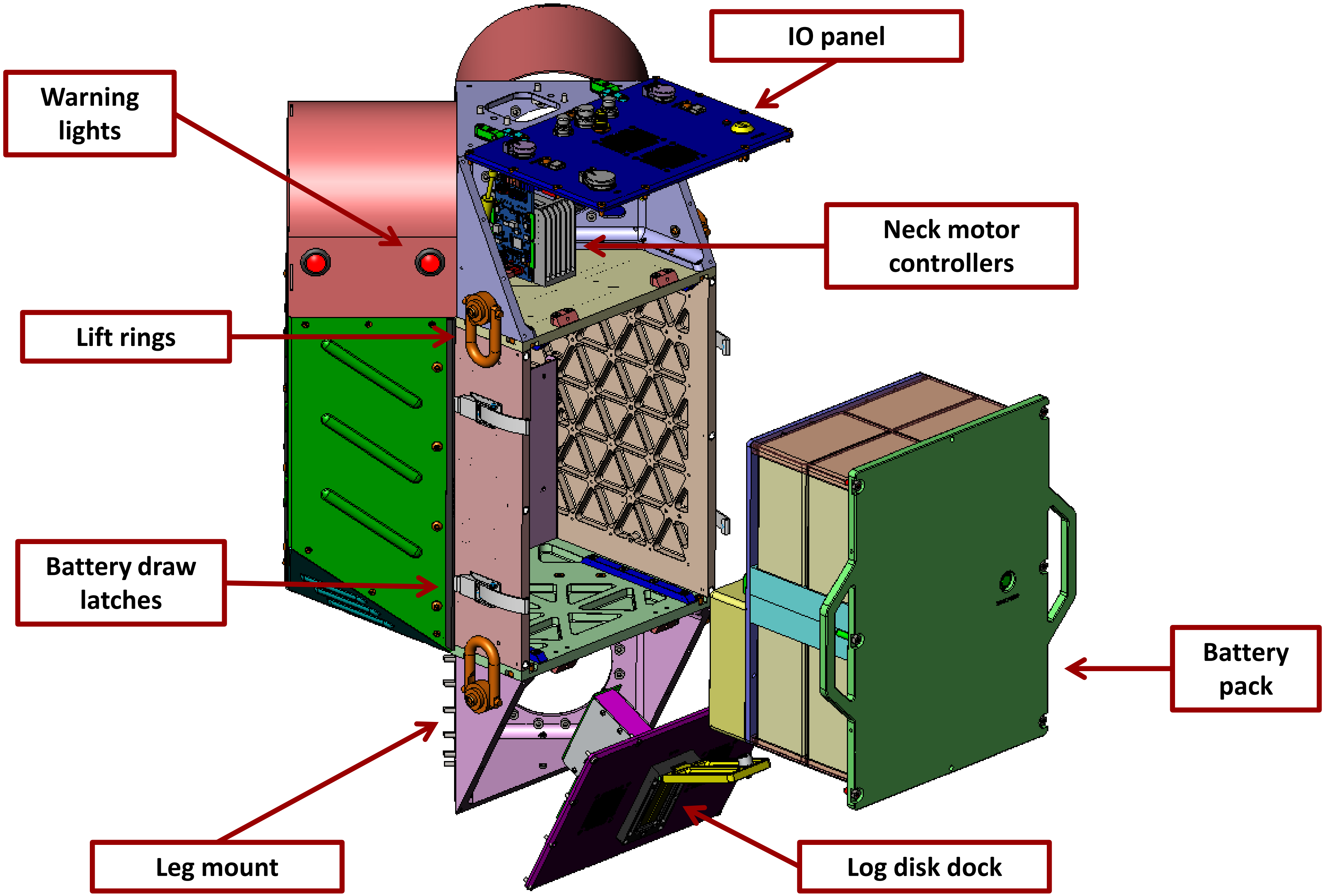
Torso Overview

- **Provide rigid structural support to limbs**
- **Package and protect internal electronics**
  - Power conditioning and distribution
  - Positioning
  - Computing
  - Joint 1 motor controllers
- **Maximize workspace**

Torso Details



Torso Details



CHIMP Mass Distribution

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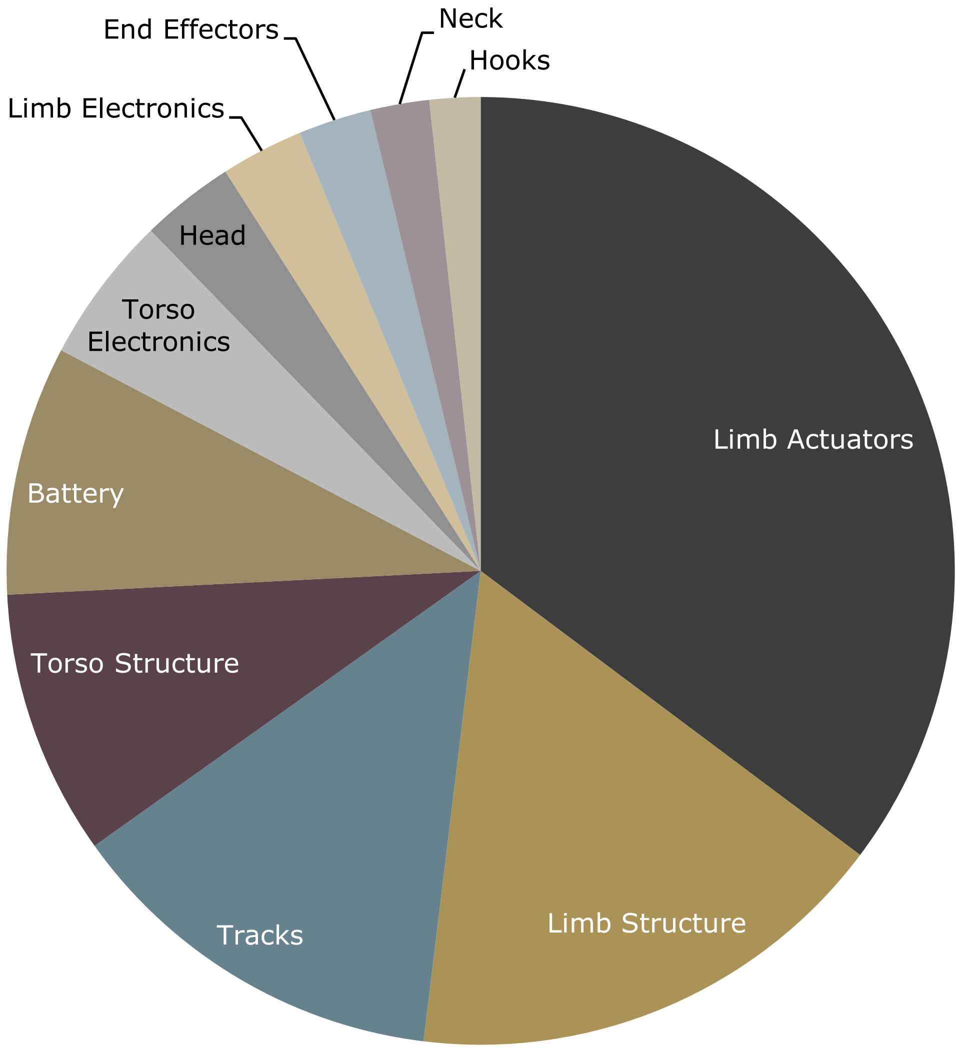

	Mass (kg)	Qty	Sub-Total
Limb Actuators	2.5	26	65
Limb Structure	7.7	4	30.8
Tracks	6.1	4	24.4
Torso Structure	16.7	1	16.7
Battery	15.7	1	15.7
Torso Electronics	9.3	1	9.3
Head	5.9	1	5.9
Limb Electronics	1.3	4	5.2
End Effectors	2.3	2	4.6
Neck	3.7	1	3.7
Hooks	0.8	4	3.2

Total	184.5

Drive Joint Modules

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Kollmorgen AKM Servo Motor

- Zero backlash
- Torque and power density
- Overload clutch
- Spring compliance
- Absolute position
- Through cabling
- Integrated controller
- Integrated brake
- Continuous rotation
- Torque sensing

Harmonic Drive Actuators

green	Zero backlash
yellow	Torque and power density
red	Overload clutch
red	Spring compliance
green	Absolute position
green	Through cabling
red	Integrated controller
red	Integrated brake
green	Continuous rotation
red	Torque sensing

Schunk Powercube

	Zero backlash
	Torque and power density
	Overload clutch
	Spring compliance
	Absolute position
	Through cabling
	Integrated controller
	Integrated brake
	Continuous rotation
	Torque sensing

NREC Drive Joint

Green	Zero backlash
Green	Torque and power density
Green	Overload clutch
Green	Spring compliance
Green	Absolute position
Green	Through cabling
Yellow	Integrated controller
Green	Integrated brake
Green	Continuous rotation
Yellow	Torque sensing

Features - HD Drive Joint

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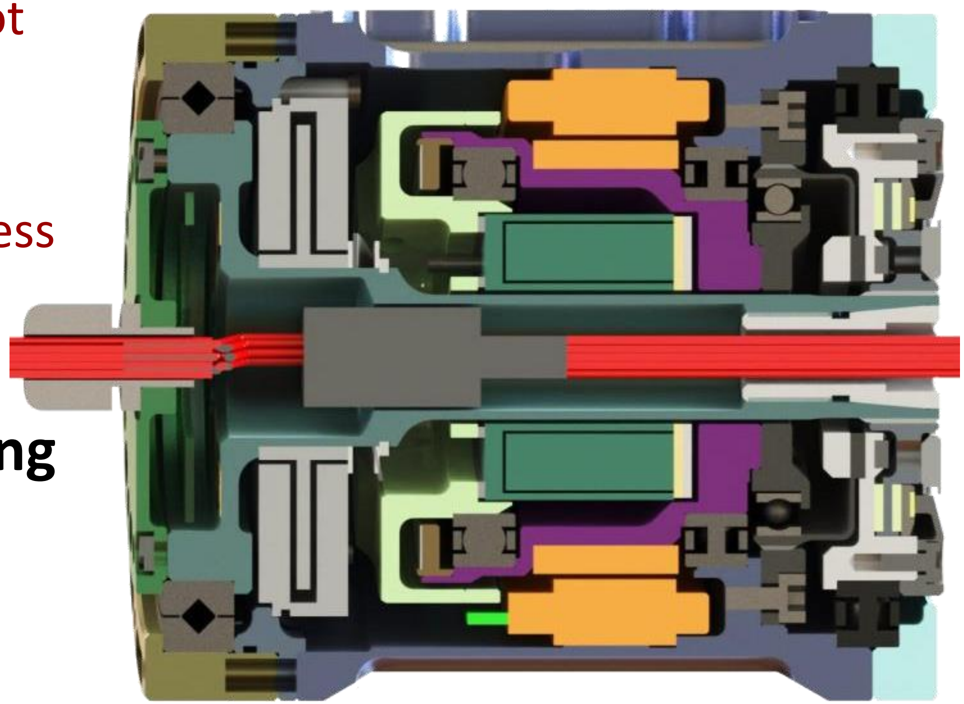
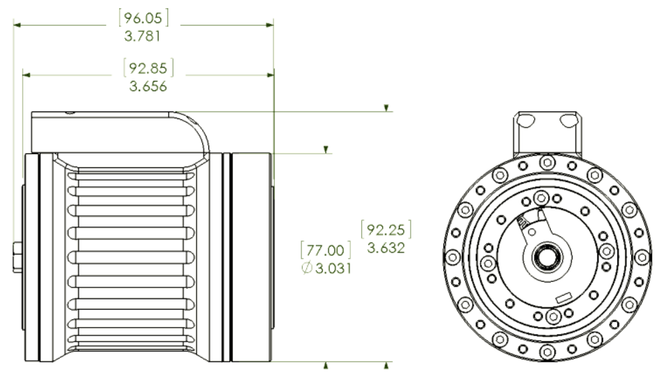
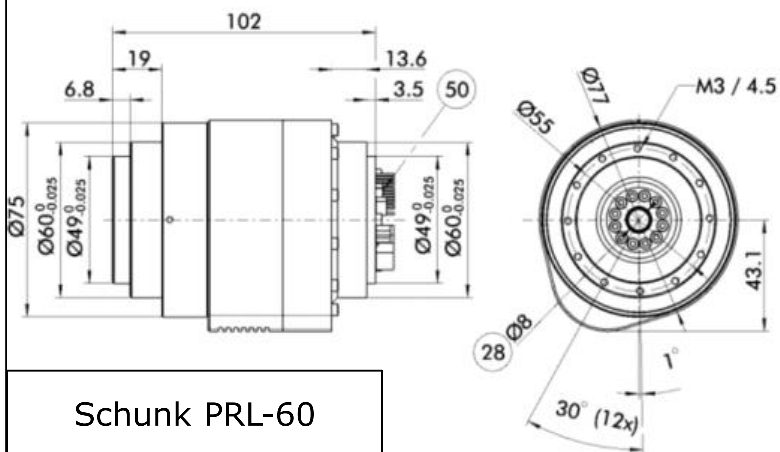
- **Zero backlash**
  - Ensures high precision and accuracy
- **High power to weight ratio**
  - 14x higher than comparables
- **Overload clutch protection**
  - Protects environment and robot
- **Spring compliance**
  - Allows for force sensing
  - Allows for positioning forgiveness
- **Absolute position encoder**
  - Always know where we are
- **Through hole for cable routing**
  - Ease of interconnections
- **Continuous rotation**



NREC Drive Joint vs. Schunk Powercube

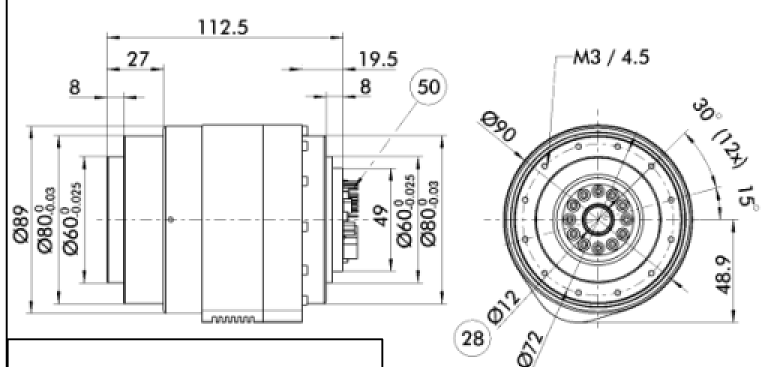


NREC NGT-20



Schunk PRL-60

		NGT-20	PRL-60	PRL-80
Torque per kg	NM/kg	15.9	4.5	17.3
Power per kg	W/kg	50.0	3.9	7.6
Torque per liter	Nm/liter	38.0	9.5	28.9



Schunk PRL-80

NREC Drive Joint

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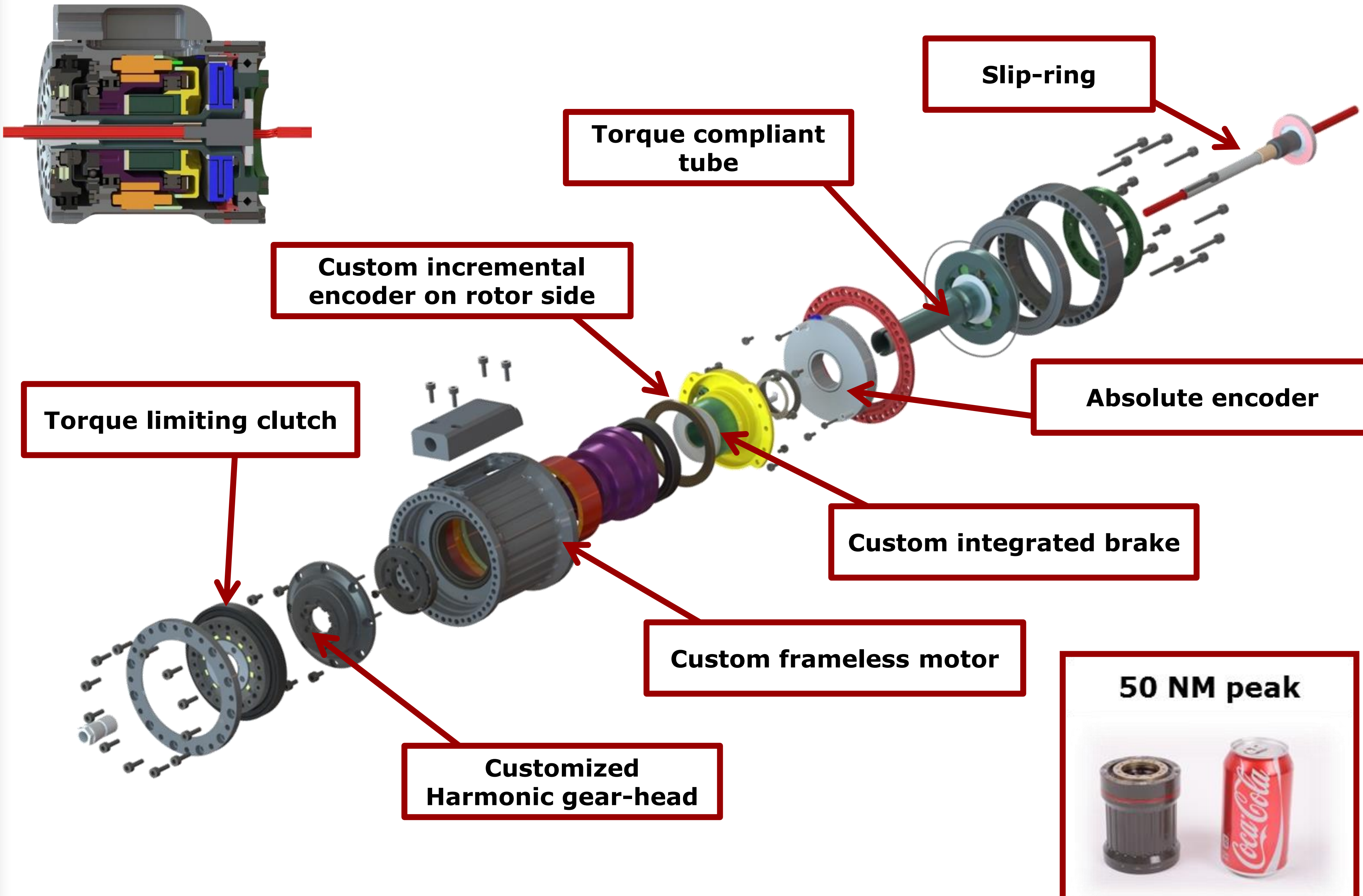
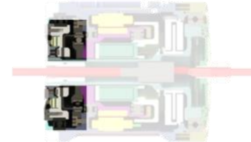


Torque Limiting Clutch



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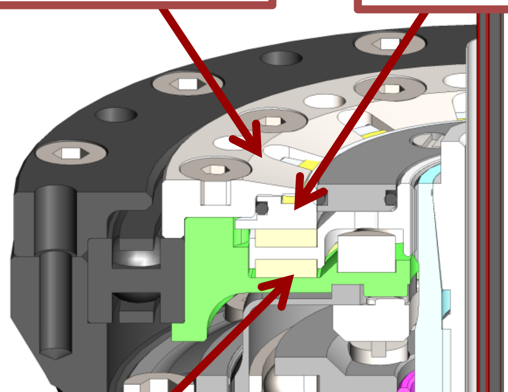
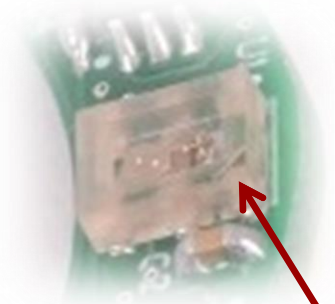


		NGT-20	NGT-50	NGT-100	NGT-200
Design Holding Torque	NM	50	175	380	700
Compressive Force Required	N	2638	7528	13642	18739
Pressure on Clutch	psi	748	1379	1886	1349
During assembly clutches are set to +- 10% of Desired Holding Torque					

Incremental Encoders



Custom incremental encoder disks

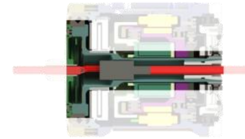
Custom encoder read head

Avago AEDR-8300-1Wx

Encoder electronics integrated into brake housings

Encoder disks mounted or rotor shafts

Torque Tubes



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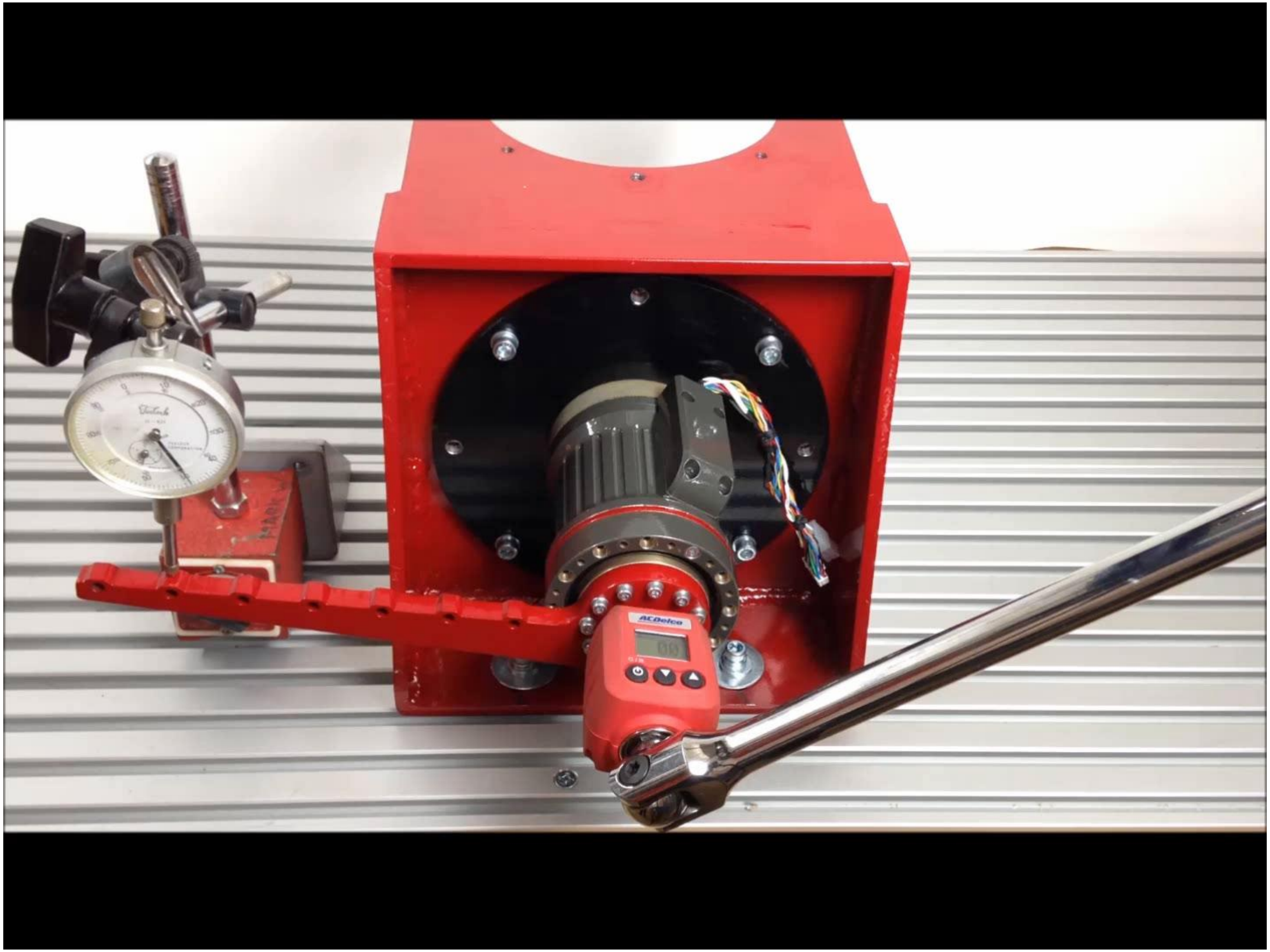
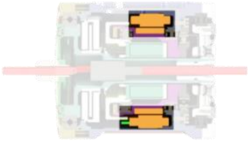
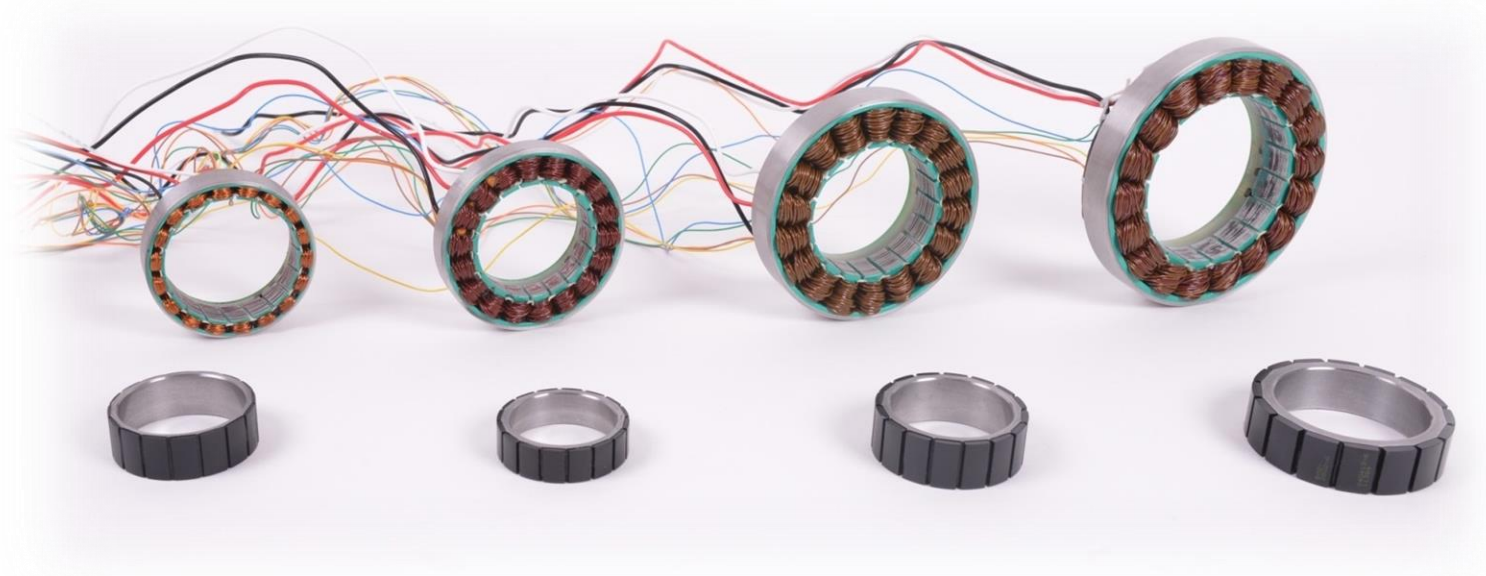
		NGT-20	NGT-50	NGT-100	NGT-200
Test torque	**NM**	30	150	230	550
Angular deflection	**Degrees**	0.98	1.55	1.34	1.46
Torque spring constant	**NM/deg**	30.6	96.8	171.6	378.0

Torque Tubes Testing



Frameless Motors





		NGT-20	NGT-50	NGT-100	NGT-200
Manufacturer	-	KOLLMORGEN	KOLLMORGEN	KOLLMORGEN	KOLLMORGEN
Part number	-	BM-19XX/NGT-20	BM-18XX/NGT-50	BM-21XX/NGT-100	BM-27XX/NGT-200
Torque constant	Nm/arms	0.2	0.1	0.2	0.2
Continuous torque	Nm	0.29	0.75	2.10	2.10
Peak torque	Nm	0.7	1.9	3.0	5.5
Motor RPM (continuous torque)	rpm	2998	4333	3049	2961
Number of poles	-	16	16	16	16

CHIMP Modularity

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Category	Quantity 14	Quantity 2000
Absolute Encoder	$ 845.00	$ 42.50
Base Unit	$ 1,557.50	$ 277.50
Bearings	$ 240.00	$ 108.00
Brake	$ 279.19	$ 28.65
Clutch	$ 305.00	$ 44.00
Hardware	$ 110.25	$ 13.80
Harmonic Drive	$ 1,000.00	$ 250.00
Incromental Encoder	$ 237.75	$ 43.50
Motor	$ 1,700.00	$ 350.00
Slip Ring	$ 346.00	$ 85.85
Torque Tube	$ 621.57	$ 121.50
Motor Controller	$ 1,200.00	$ 200.00
Total Fab	**$ 8,442.26**	**$ 1,565.30**
Mechanical Tech	$ 20.00	$ 8.00
Electrical Tech	$ 5.00	$ 2.50
Total Labor	**$ 1,500.00**	**$ 630.00**
Total Cost	**$ 9,942.26**	**$ 2,195.30**

CHIMP Sensor Head

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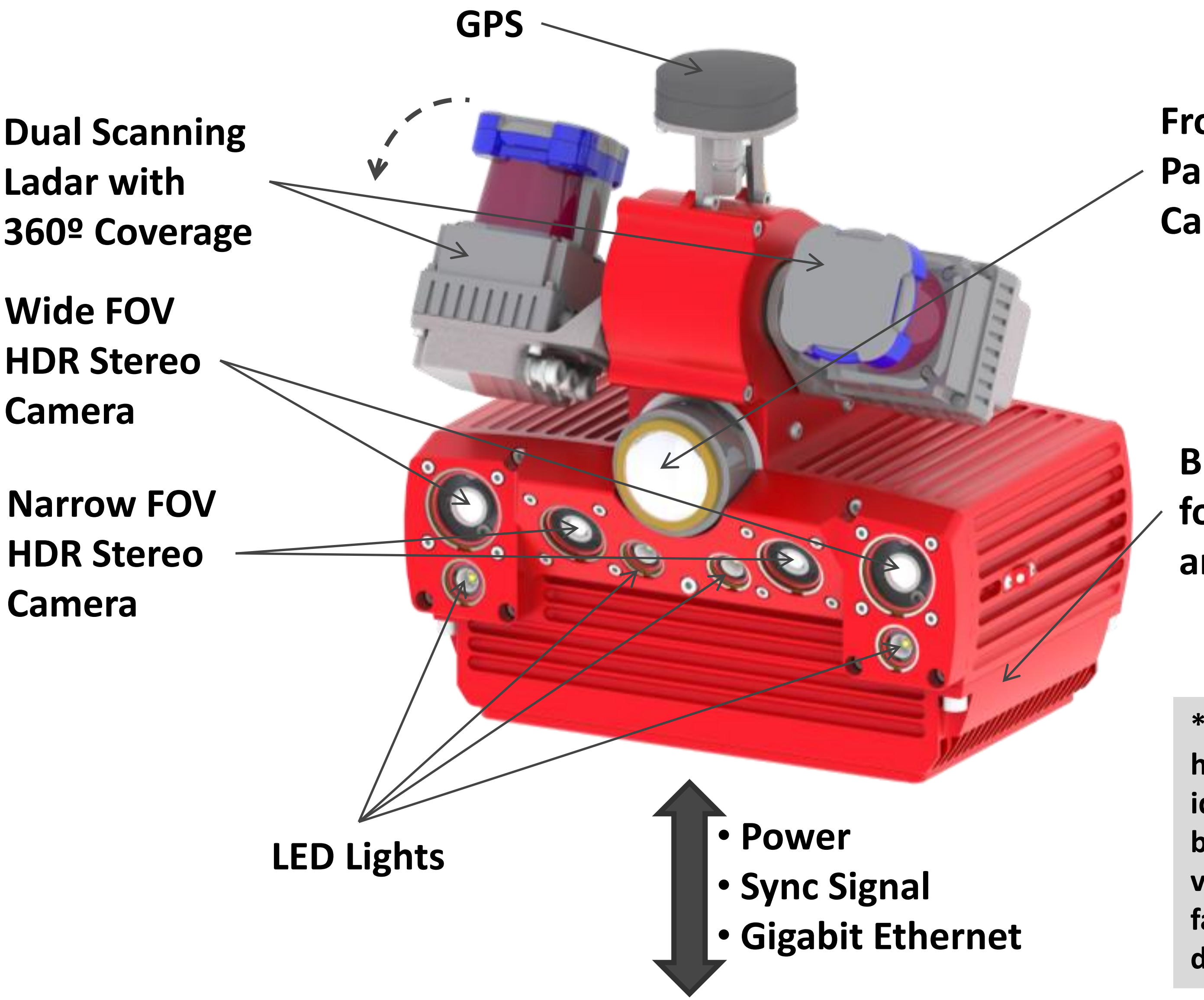
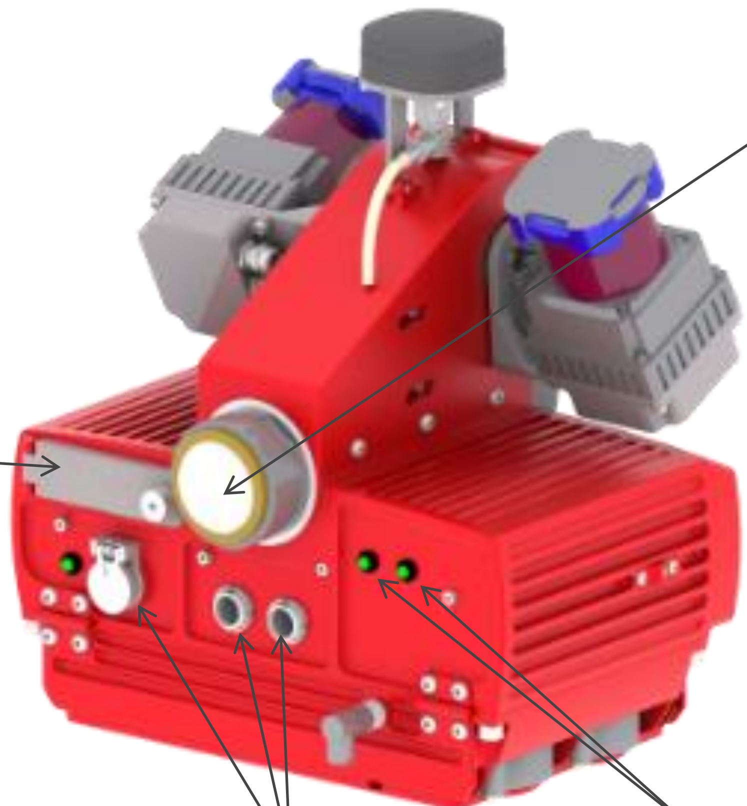
Overall Design: Front View



* A surrogate sensor head with all the identical sensors was built in early 2013 to validate the design and facilitate software development

Overall Design: Rear View



Rear Panomorphic/Fisheye Cameras

Access Door to the Log Drive

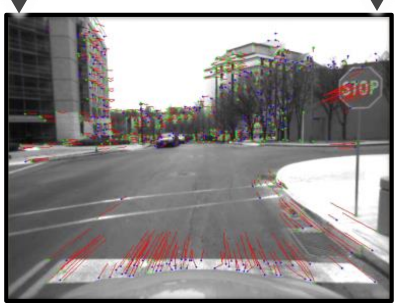
Diagnostic LEDs

I/O Connectors for Diagnostic

Dual Stereo Usage

Wide Baseline
Wide FOV
Stereo

Stereo Based
Visual Odometry



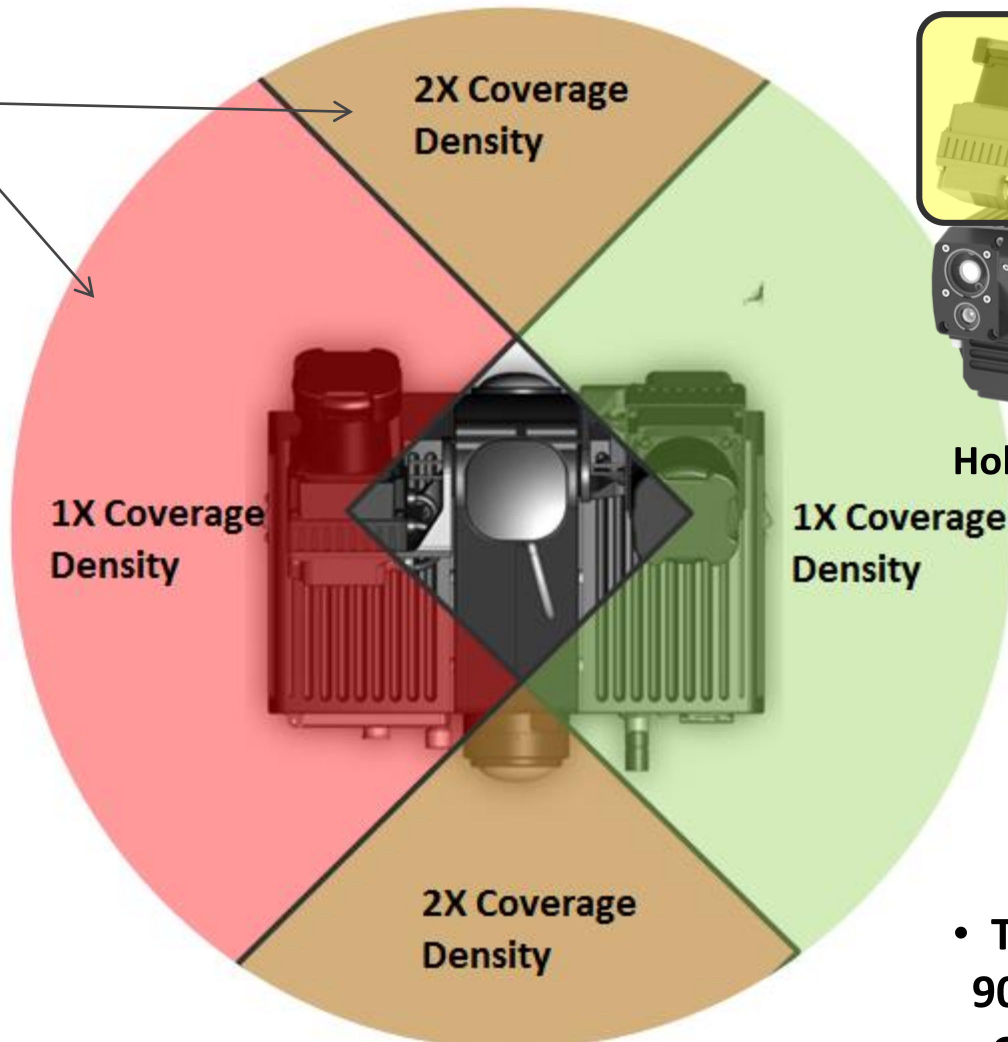
Narrow Baseline
Narrow FOV
Stereo

- Foveal stereo provides higher resolution stereo in a narrower FOV
- Roughly the same baseline as human eyes -> enable direct stereo display
- Tilted 25 degrees down to improve downward visibility for manipulation tasks

The horizontal orientation of the wide FOV stereo is optimized for VisOdo, while the 25° down tilt of the narrow FOV stereo is optimized for looking at various manipulation tasks such as driving

Dual Scanning Ladar

The dual ladar arrangement double the density/frame rate of the front and back area, which are the most important area for manipulation and navigation

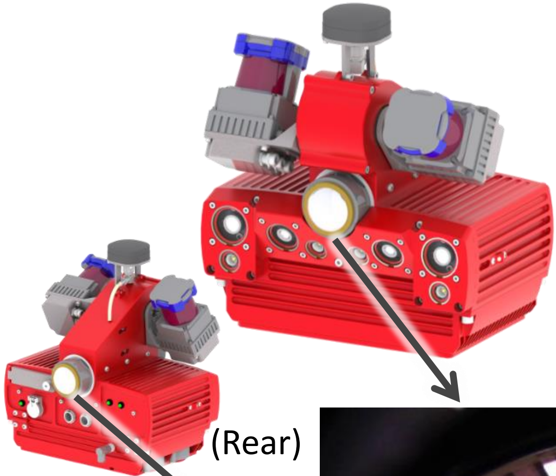


Hokuyo UTM-30LX-EW:

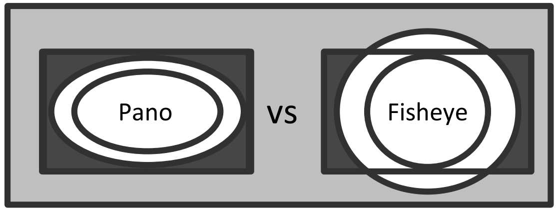
- Measuring distance: 0.1 – 30 meters
- Accuracy: 30 – 50 mm
- Angular resolution: 0.25°
- Update rate: 40Hz
- Horizontal FOV: 270 degrees

- **Two units mounted 90° off-phase**
- **Capable of continuous rotation**

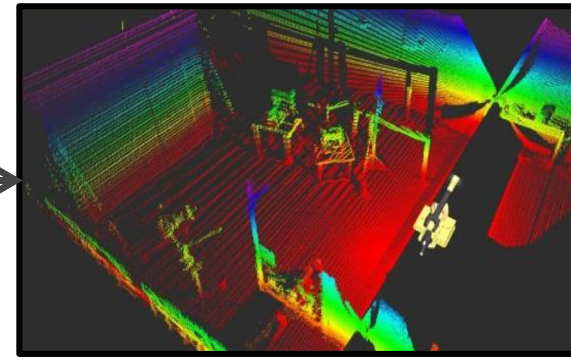
Panomorphic Cameras Output



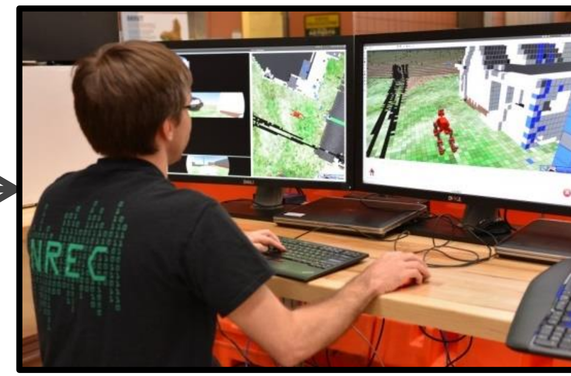
(Rear)



Laser Colorization



OCU Visualization



Front and rear panomorphic cameras provide 360° of visibility. These cameras are used to colorize the laser scans and to provide the OCU operator with situational awareness.

Finished Head: External Front View

Finished Head: Internal View