CHIMP: CMU Highly Intelligent Mobile Platform

Eric Meyhofer
Modular Robotics
November 2014
Carnegie Mellon University - NREC

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

Pittsburgh, Pennsylvania

School of Computer Science
Topics

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

INTERACTIVE USER INTERFACE
- IMMERSIVE ENVIRONMENT
- TASK SELECTION
- PLANNING STACK
- VIRTUAL FIXTURING METHODS
- PLANNING LIBRARY
- TELEOP CONTROL

PERCEPTION
- WORLD MODELING
  - VOLUMETRIC MODELS
  - EMBEDDED POSE SYSTEM
- POSITIONING
  - STATE ESTIMATION

PLANNING
- PLANNING LIBRARY
  - CORE FUNCTIONALITY
  - PLAANNERS
  - STATE FESIBILITY CHECKER
- PLANNING STACK
  - DISMOUNTED MOBILITY PLANNING
  - MANIPULATION PLANNING
  - MOUNTED MOBILITY PLANNING

CONTROL
- ROBOT ARBITER
  - TASK SPECIFIC MODES
- CONTROL CORRECTION / ADJUSTMENT
  - CHIMP DRIVER
  - Trajectory Plugins
  - Reactive Behaviors
  - Feedforward Plugins
  - Feedback Plugins
  - Robot Plugins

SENSING
- SENSOR HEAD
  - BODY SENSORS
- LIMB SENSORS

ACTUATION
- GRIPPERS
  - AUXILIARY ACTUATORS
- LIMB ACTUATORS
Development Strategy

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

Work in parallel
Hardware Development

DARPA Robotics Challenge

PIs: Tony Stentz, Alonzo Kelly, Herman Herman, Eric Meyhofer
Systems Lead: David Stager

DARPA PM: Dr. Gill Pratt

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CHIMP Mechanical Design
Mechanical Design Overview

- Multi-modal sensor head
- Torso with integrated computing, positioning, networking, and power electronics
- Common drive joint module
- 7 DOF arm (3-1-3)
- Foot paddles
- Actuated climbing hooks
- Gripper with 6 DOF force-torque sensor

**Physical**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>185 kg (407 lb.)</td>
</tr>
<tr>
<td>Standing Height</td>
<td>160 cm (5.2’)</td>
</tr>
<tr>
<td>Crawling Height</td>
<td>120 cm (3.9’)</td>
</tr>
<tr>
<td>Shoulder/Hip Width</td>
<td>74 cm (29”)</td>
</tr>
</tbody>
</table>
Mechanical Design Overview

- IO panel
- 2 DOF Neck
- Field replaceable battery pack
- 6 DOF leg (3-1-2)
- Removable data logs
- Custom drive tracks
Mechanical Design Evolution

Proposal Concept

Offset Joints

Fixed Waist

Diff. Drive

Harmonic Drive Joints

Limb Detail

Torso Iteration

Nested Track

Torso Detail

Tasks Completion
## Final Mechanical Design

<table>
<thead>
<tr>
<th>Head Sensor</th>
<th>Limb Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 LIDAR (nodding)</td>
<td>Stereo camera pair</td>
</tr>
<tr>
<td>2 panamorphic cameras</td>
<td>Illuminator</td>
</tr>
<tr>
<td>2 stereo camera pairs</td>
<td>Illuminator</td>
</tr>
<tr>
<td>GPS receiver</td>
<td></td>
</tr>
</tbody>
</table>

### Degrees of Freedom

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Data/Signal/Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>45 total:</td>
<td>Control</td>
</tr>
<tr>
<td>14 in 2 arms (7 per)</td>
<td>RC, TeleOp, Autonomous</td>
</tr>
<tr>
<td>12 in 2 legs (6 per)</td>
<td>Encoders</td>
</tr>
<tr>
<td>2 neck (head twist &amp; lift)</td>
<td>18 bits absolute</td>
</tr>
<tr>
<td>1 LIDAR (nodding)</td>
<td>Computing</td>
</tr>
<tr>
<td>8 in 2 grippers (4 per)</td>
<td>Intel Core i7 3820QM</td>
</tr>
<tr>
<td>4 in 4 tracks (1 per)</td>
<td>(2 torso, 1 head)</td>
</tr>
<tr>
<td>4 in 4 hooks (1 per)</td>
<td>Data</td>
</tr>
<tr>
<td></td>
<td>GigE, CAN</td>
</tr>
<tr>
<td>Joint Modules</td>
<td>Communication</td>
</tr>
<tr>
<td>4 sizes, clutched</td>
<td>WiFi</td>
</tr>
<tr>
<td>Grippers</td>
<td>Status</td>
</tr>
<tr>
<td>Robotiq 3-Finger Adaptive</td>
<td>LED Indicators</td>
</tr>
</tbody>
</table>

### Electrical

<table>
<thead>
<tr>
<th>Electrical</th>
<th>Environmental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Voltage</td>
<td>Protection</td>
</tr>
<tr>
<td>60 VDC</td>
<td>IP 52 (dust protection; water drip)</td>
</tr>
<tr>
<td>Batteries</td>
<td>Ambient Temp.</td>
</tr>
<tr>
<td>BB-2590 Li-Ion (4P-2S)</td>
<td>38 °C (100 °F)</td>
</tr>
<tr>
<td>Battery Energy</td>
<td>Cooling</td>
</tr>
<tr>
<td>2.4 kWh</td>
<td>Forced air and natural convection</td>
</tr>
<tr>
<td>Shunt</td>
<td></td>
</tr>
<tr>
<td>NREC Custom</td>
<td></td>
</tr>
<tr>
<td>Charger</td>
<td></td>
</tr>
<tr>
<td>Off-board</td>
<td></td>
</tr>
<tr>
<td>APU</td>
<td></td>
</tr>
<tr>
<td>Off-board 600 Wh</td>
<td></td>
</tr>
</tbody>
</table>

### Physical

| 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

- Slip ring output
- Controller
- Slip ring input
- Joint control
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 Drive Actuator

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous torque</td>
<td>Nm</td>
<td>15.0</td>
</tr>
<tr>
<td>Speed (continuous torque)</td>
<td>m/s</td>
<td>1.30</td>
</tr>
<tr>
<td>Power (continuous torque)</td>
<td>W</td>
<td>330</td>
</tr>
<tr>
<td>Peak torque</td>
<td>Nm</td>
<td>42</td>
</tr>
<tr>
<td>Speed (peak torque)</td>
<td>m/s</td>
<td>1.1</td>
</tr>
<tr>
<td>Power (peak torque)</td>
<td>W</td>
<td>750</td>
</tr>
</tbody>
</table>
Track Drive Actuator

- Track guide
- Cogged track interface
- Custom brake
- Incremental encoder
- 21:1 Planetary gearbox
- Frameless motor
- Replaceable pinion gear
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

- Removable covers
- Sealed computing module
- Internal storage disks
- IMU
- Power conversion and resistors
- Heat sink and fuse access panel
- Arm mount
Torso Details

- Warning lights
- Lift rings
- Battery draw latches
- Leg mount
- IO panel
- Neck motor controllers
- Battery pack
- Log disk dock
Drive Joint Modules
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

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

<table>
<thead>
<tr>
<th>Feature</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero backlash</td>
<td>✔</td>
</tr>
<tr>
<td>Torque and power density</td>
<td>✔</td>
</tr>
<tr>
<td>Overload clutch</td>
<td>✔</td>
</tr>
<tr>
<td>Spring compliance</td>
<td>✔</td>
</tr>
<tr>
<td>Absolute position</td>
<td>✔</td>
</tr>
<tr>
<td>Through cabling</td>
<td>✔</td>
</tr>
<tr>
<td>Integrated controller</td>
<td>![ ]</td>
</tr>
<tr>
<td>Integrated brake</td>
<td>![ ]</td>
</tr>
<tr>
<td>Continuous rotation</td>
<td>✔</td>
</tr>
<tr>
<td>Torque sensing</td>
<td>![ ]</td>
</tr>
</tbody>
</table>
Features - HD Drive Joint

• 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

<table>
<thead>
<tr>
<th></th>
<th>NGT-20</th>
<th>PRL-60</th>
<th>PRL-80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque per kg</td>
<td>15.9</td>
<td>4.5</td>
<td>17.3</td>
</tr>
<tr>
<td>Power per kg</td>
<td>50.0</td>
<td>3.9</td>
<td>7.6</td>
</tr>
<tr>
<td>Torque per liter</td>
<td>38.0</td>
<td>9.5</td>
<td>28.9</td>
</tr>
</tbody>
</table>

NREC Drive Joint

- Custom frameless motor
- Customized Harmonic gear-head
- Custom integrated brake
- Absolute encoder
- Slip-ring
- Torque compliant tube
- Custom incremental encoder on rotor side
- Torque limiting clutch
- 50 NM peak
# Torque Limiting Clutch

During assembly clutches are set to ±10% of Desired Holding Torque.

<table>
<thead>
<tr>
<th></th>
<th>NGT-20</th>
<th>NGT-50</th>
<th>NGT-100</th>
<th>NGT-200</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design Holding Torque</strong></td>
<td>NM</td>
<td>50</td>
<td>175</td>
<td>380</td>
</tr>
<tr>
<td><strong>Compressive Force Required</strong></td>
<td>N</td>
<td>2638</td>
<td>7528</td>
<td>13642</td>
</tr>
<tr>
<td><strong>Pressure on Clutch</strong></td>
<td>psi</td>
<td>748</td>
<td>1379</td>
<td>1886</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>NGT-20</th>
<th>NGT-50</th>
<th>NGT-100</th>
<th>NGT-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test torque</td>
<td>NM</td>
<td>30</td>
<td>150</td>
<td>230</td>
</tr>
<tr>
<td>Angular deflection</td>
<td>NM/deg</td>
<td>0.98</td>
<td>1.55</td>
<td>1.34</td>
</tr>
<tr>
<td>Torque spring constant</td>
<td>NM/deg</td>
<td>30.6</td>
<td>96.8</td>
<td>171.6</td>
</tr>
</tbody>
</table>

Torque Tubes Testing
Frameless Motors

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>NGT-20</th>
<th>NGT-50</th>
<th>NGT-100</th>
<th>NGT-200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part number</td>
<td>BM-19XX/NGT-20</td>
<td>BM-18XX/NGT-50</td>
<td>BM-21XX/NGT-100</td>
<td>BM-27XX/NGT-200</td>
</tr>
<tr>
<td>Torque constant (Nm/arms)</td>
<td>0.2</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Continuous torque (Nm)</td>
<td>0.29</td>
<td>0.75</td>
<td>2.10</td>
<td>2.10</td>
</tr>
<tr>
<td>Peak torque (Nm)</td>
<td>0.7</td>
<td>1.9</td>
<td>3.0</td>
<td>5.5</td>
</tr>
<tr>
<td>Motor RPM (continuous torque)</td>
<td>2998</td>
<td>4333</td>
<td>3049</td>
<td>2961</td>
</tr>
<tr>
<td>Number of poles</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
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</table>
CHIMP Modularity

<table>
<thead>
<tr>
<th>Category</th>
<th>Quantity 14</th>
<th>Quantity 2000</th>
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<tbody>
<tr>
<td>Absolute Encoder</td>
<td>$845.00</td>
<td>$42.50</td>
</tr>
<tr>
<td>Base Unit</td>
<td>$1,557.50</td>
<td>$277.50</td>
</tr>
<tr>
<td>Bearings</td>
<td>$240.00</td>
<td>$108.00</td>
</tr>
<tr>
<td>Brake</td>
<td>$279.19</td>
<td>$28.65</td>
</tr>
<tr>
<td>Clutch</td>
<td>$305.00</td>
<td>$44.00</td>
</tr>
<tr>
<td>Hardware</td>
<td>$110.25</td>
<td>$13.80</td>
</tr>
<tr>
<td>Harmonic Drive</td>
<td>$1,000.00</td>
<td>$250.00</td>
</tr>
<tr>
<td>Incremental Encoder</td>
<td>$237.75</td>
<td>$43.50</td>
</tr>
<tr>
<td>Motor</td>
<td>$1,700.00</td>
<td>$350.00</td>
</tr>
<tr>
<td>Slip Ring</td>
<td>$346.00</td>
<td>$85.85</td>
</tr>
<tr>
<td>Torque Tube</td>
<td>$621.57</td>
<td>$121.50</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>$1,200.00</td>
<td>$200.00</td>
</tr>
<tr>
<td>Total Fab</td>
<td>$8,442.26</td>
<td>$1,565.30</td>
</tr>
<tr>
<td>Mechanical Tech</td>
<td>$20.00</td>
<td>$8.00</td>
</tr>
<tr>
<td>Electrical Tech</td>
<td>$5.00</td>
<td>$2.50</td>
</tr>
<tr>
<td>Total Labor</td>
<td>$1,500.00</td>
<td>$630.00</td>
</tr>
<tr>
<td>Total Cost</td>
<td>$9,942.26</td>
<td>$2,195.30</td>
</tr>
</tbody>
</table>
CHIMP Sensor Head
Overall Design: Front View

- Dual Scanning Ladar with 360° Coverage
- Wide FOV HDR Stereo Camera
- Narrow FOV HDR Stereo Camera
- LED Lights
- Front Panomorphc/Fisheye Cameras
- Built-in Electronics for Sensor Interface and Processing
- GPS

- Power
- Sync Signal
- Gigabit Ethernet

* 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 Panomorphc/Fisheye Cameras
- Access Door to the Log Drive
- Diagnostic LEDs
- I/O Connectors for Diagnostic
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.

- 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 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
Front and rear panomorphomorphic 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: Internal View