The Development of a Robotic Platform for Deploying Science Instruments in Unstructured Terrain

Presented by

Nathanael A. Miller

This body of work is presented to the faculty of Old Dominion University in partial fulfillment of the requirements for the degree of Master of Science in Electrical and Computer Engineering

OLD DOMINION UNIVERSITY
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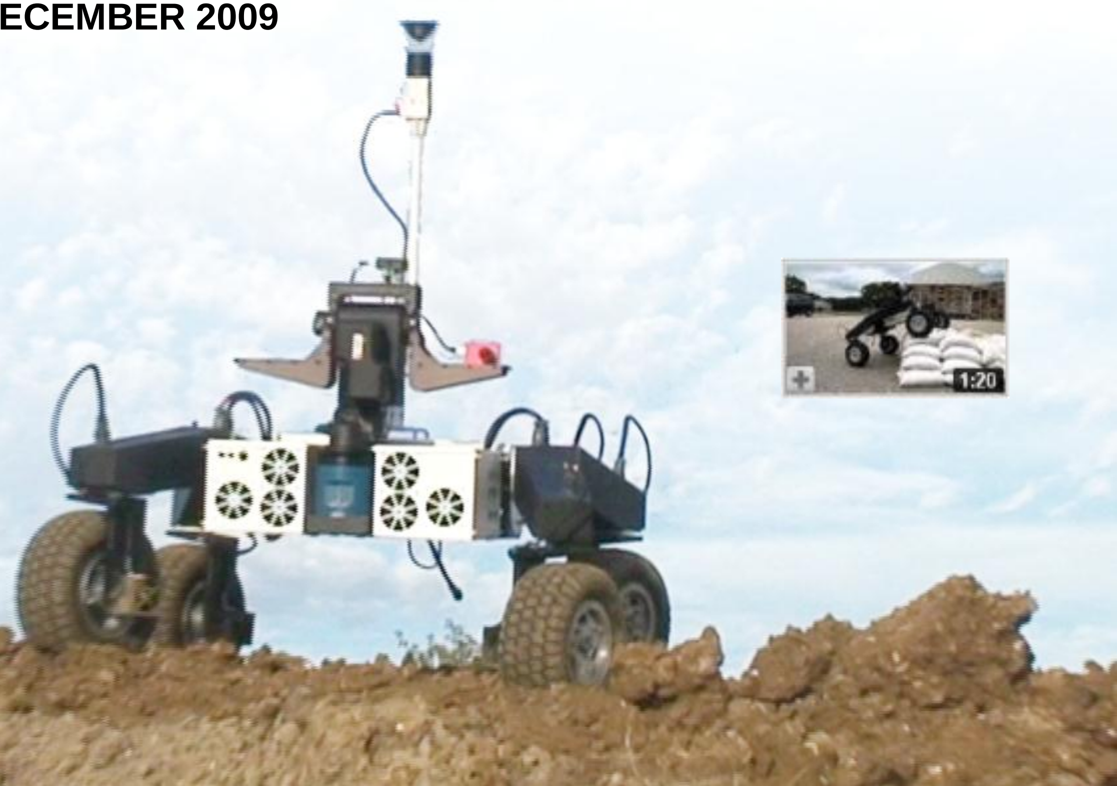


Committee

Chair: Dr. Linda L. Vahala

Members: Dr. K. Vijayan Asari

Dr. Oscar R. Gonzalez

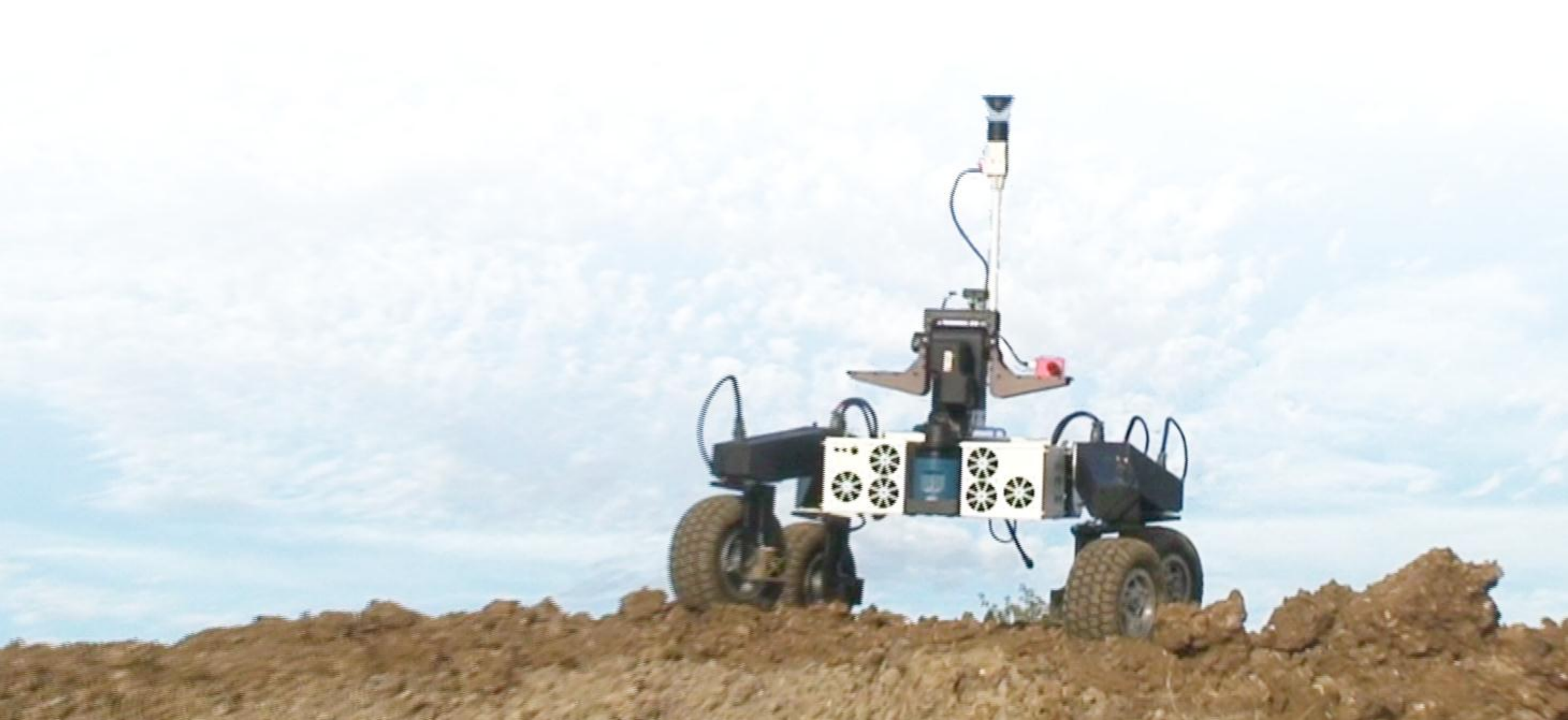
Dr. Arthur T. Bradley

Outline

- Mission, Story, and Scope
- Top-down Design
- Mechanical
- Control
- Control Implementation
- Control by Instant Centers
- Sensor Implementation
- User Interface
- Results
- Future Work
- Conclusion

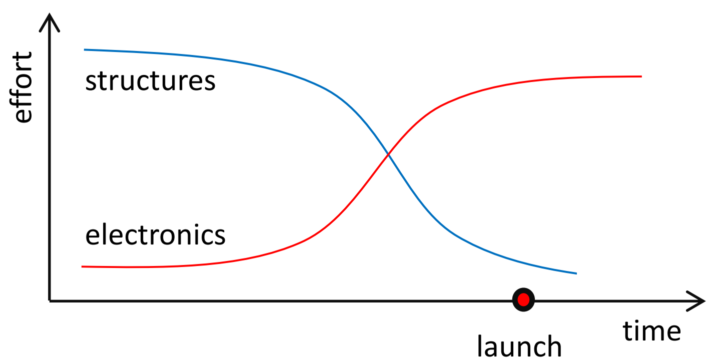
∴ more complete than thorough

Story, Scope, and Mission

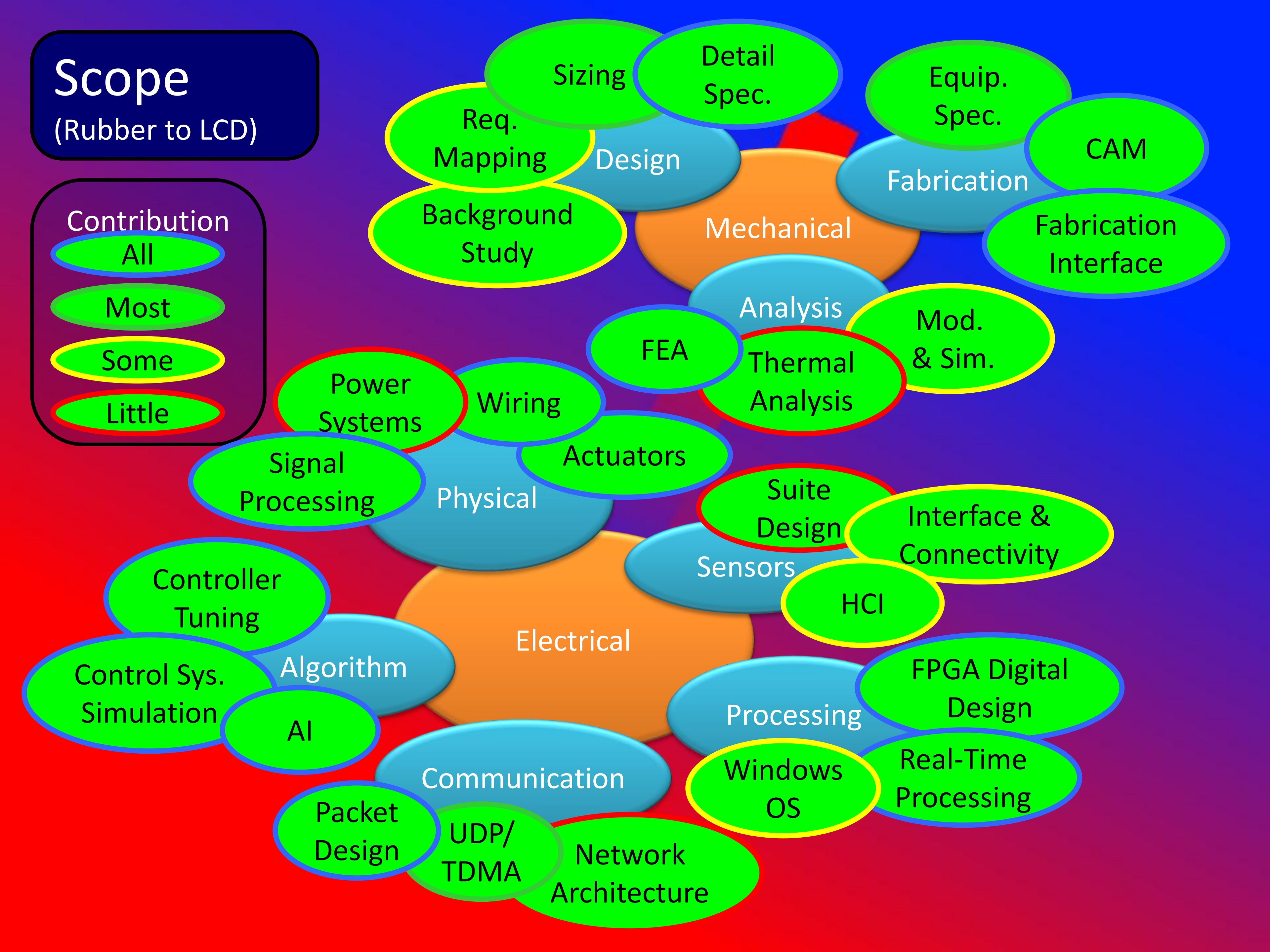


Story
(From Vision to Robot)

- Mechanical design and fabrication
- Integrate electrical system
  (read: become electrical engineer)
- Implement control system
- Develop control by method of instant centers



MAX Launch Abort System test lessons learned
- NASA Engineering Safety Center


Scope
(Rubber to LCD)
Contribution
All
Most
Some
Little
Mechanical
Design
Sizing
Detail Spec.
Req. Mapping
Background Study
Fabrication
Equip. Spec.
CAM
Fabrication Interface
Analysis
FEA
Thermal Analysis
Mod. & Sim.
Electrical
Physical
Power Systems
Wiring
Actuators
Signal Processing
Sensors
Suite Design
Interface & Connectivity
HCI
Algorithm
Controller Tuning
Control Sys. Simulation
AI
Processing
FPGA Digital Design
Real-Time Processing
Windows OS
Communication
Packet Design
UDP/ TDMA
Network Architecture

Mission
(Field a Science Instrument)

- Deploy developmental science instruments for demonstration purposes in planetary analog environments
- Develop instruments between TRL 2 and TRL 4
- Robotic experimentation and research (Autonomy/Remote presence)
- Support innovation-driven efforts with low cost to implementation

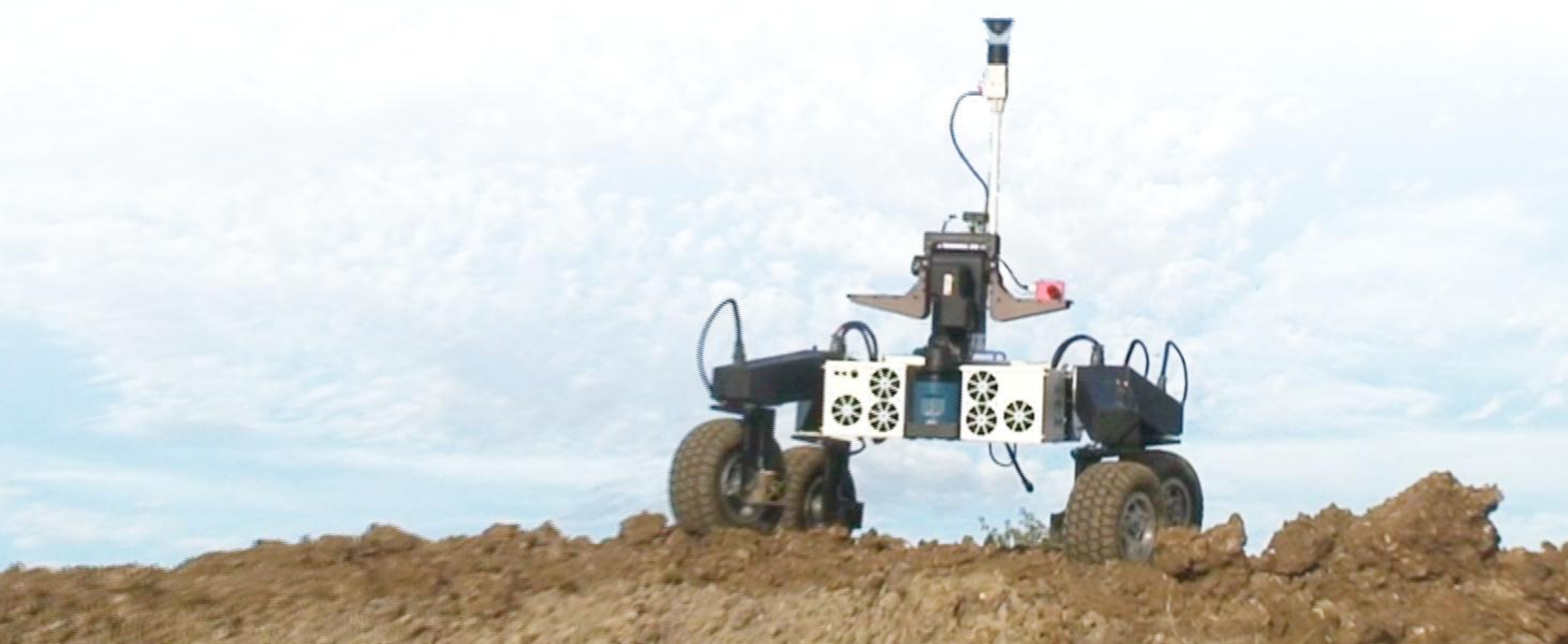
Motivation

- Planetary exploration demands mobile, autonomous, and capable robots
- Understanding the requirements
- Testing science and robotic technology

Similar Rovers

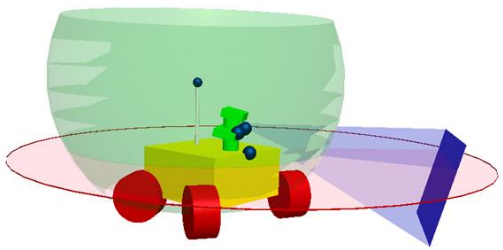
- Rocket 5, 6, and 7
- Sojourner
- MER
- MSL
- Nomad
- Scarab
- K - 10
- Chariot/Athlete

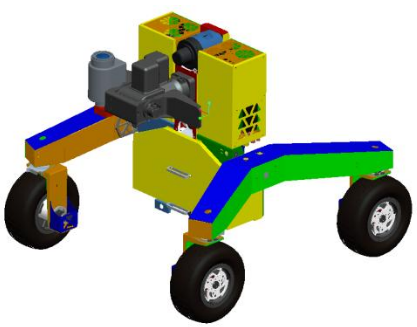
Top-down Design

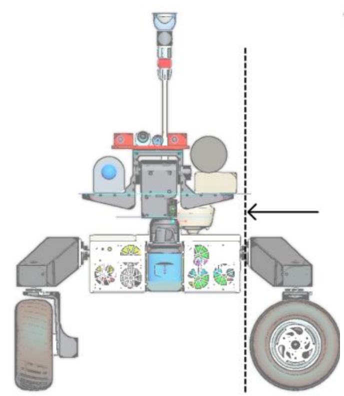


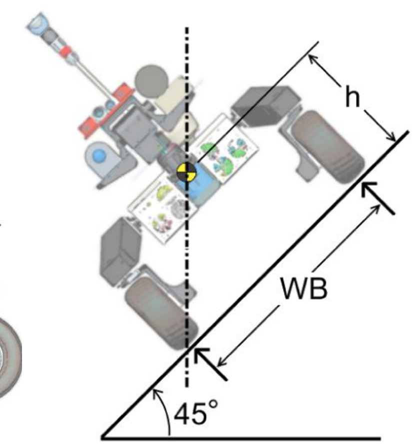
Top-down Overview
(Mobility Platform)

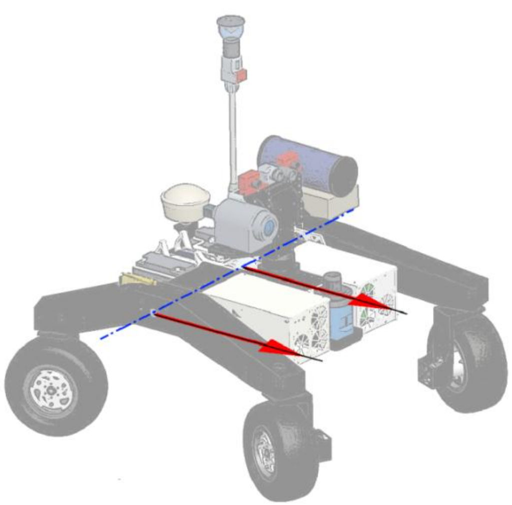
- Carry a science payload
- Omnidirectional (1:1 L:W)
- Fit through a door
- Navigate a 45° grade
- Navigate 18 inch obstacle
- Accessible electronics housing
- Sensor Needs

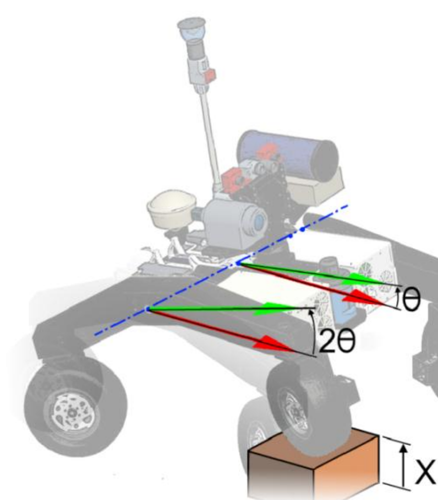


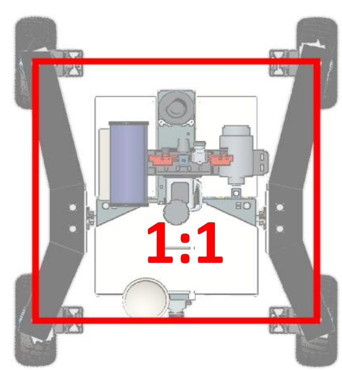












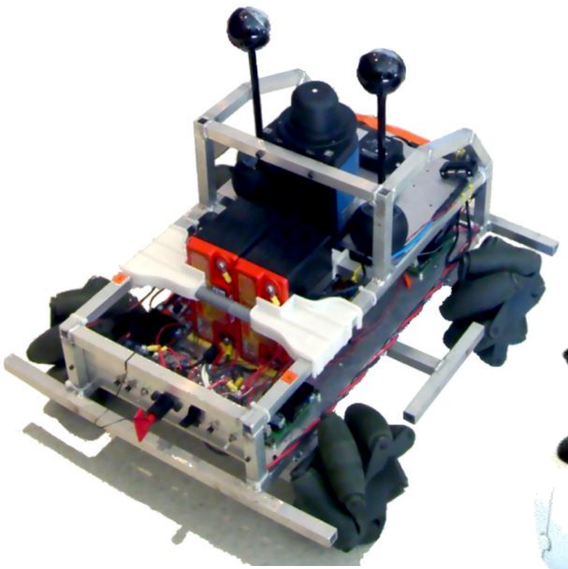
Top-down Overview
(System Architecture)

Heritage

- Sensor-rich
- Reconfigurable
- Processing-capable

Attributes

- Lots of sensor options
- IP-based communication
- Everything in LabVIEW
- Embedded PC104 processors



Top-down Overview
(Sensors)

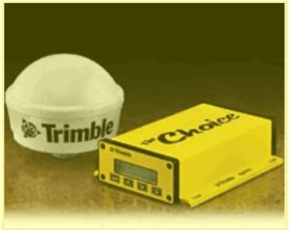
- Situational Awareness
- Target Interrogation
- Localization
- Qualitative vs. Quantitative

Directed Perception PTU-D300 Pan-Tilt

Videre Stereo Cameras

Fujinon C22x17R2-QP1™ TeleZoom CCTV Lens 22X Optical Zoom

FLIER Photon 320™ IR Thermal Imager



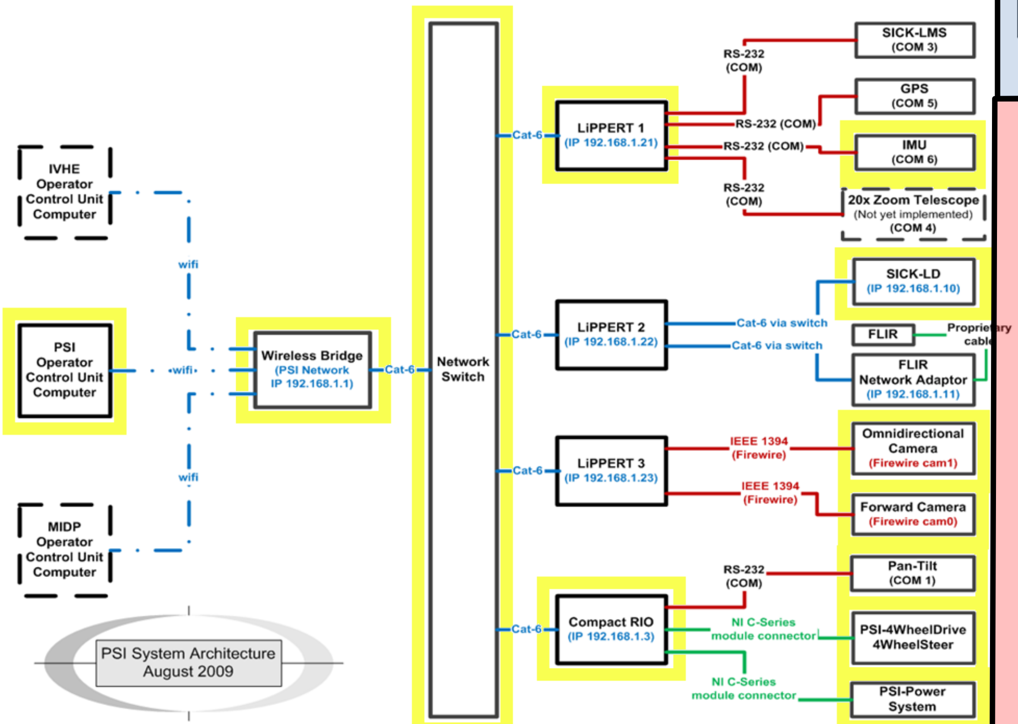
Trimble AG DGPS 132

MicroStrain 3DM-GX1 IMU Gyroscope

Hokuyo URG-04LX Laser Range-Finder

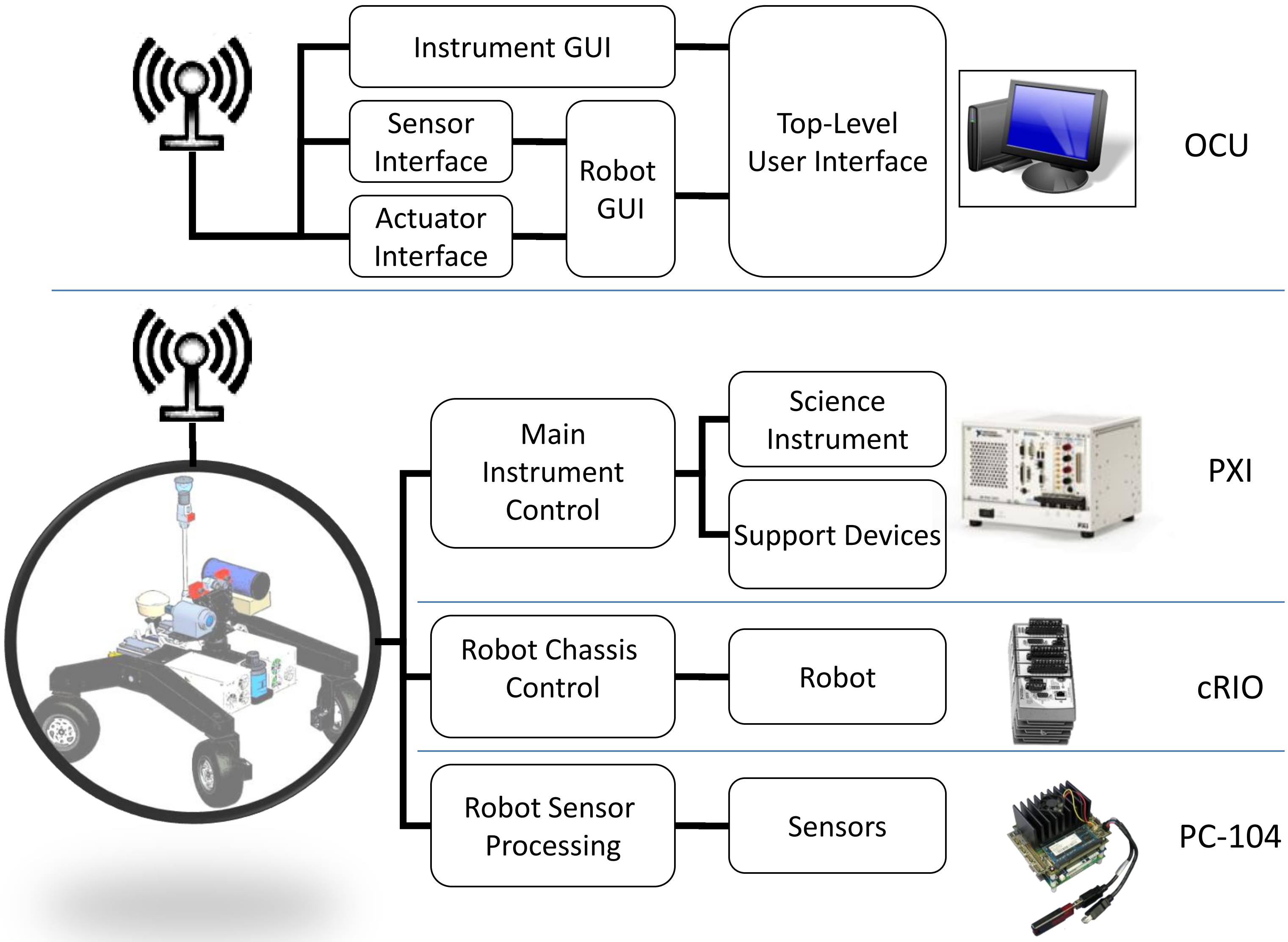
Soios 55 Omnidirectional Lens

SICK LD-OEM1000 Laser Range-Finder



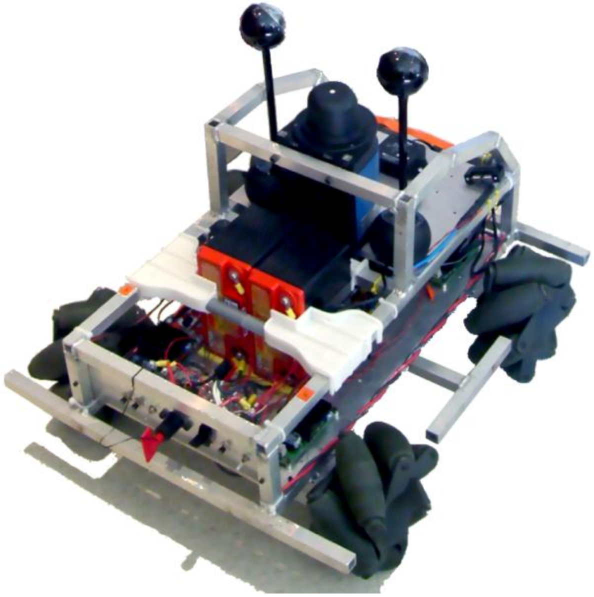
Top-down Overview
(Science Instrument)

- Modularity
- Flexibility
- Independence



Top-down Overview
(Control System)

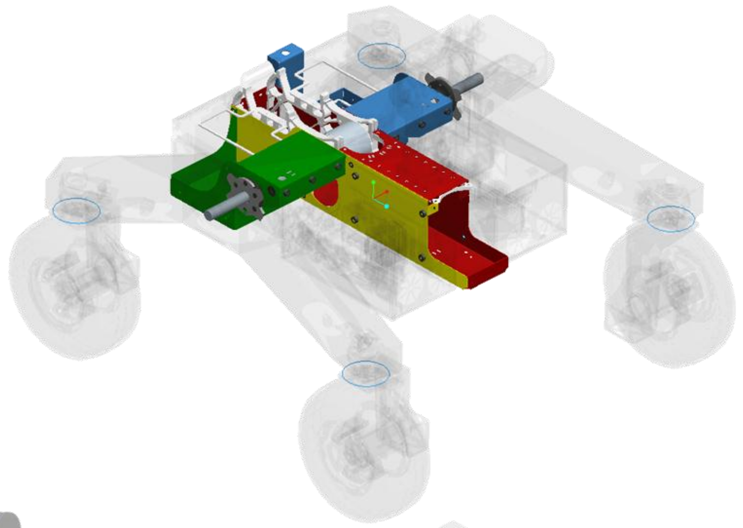
- Omnidirectional motion to an AWDAWS vehicle
- Controlled with a National Instruments Compact Rio controller with Real-Time OS, FPGA, and modular IO cards.
- Behavior-based control

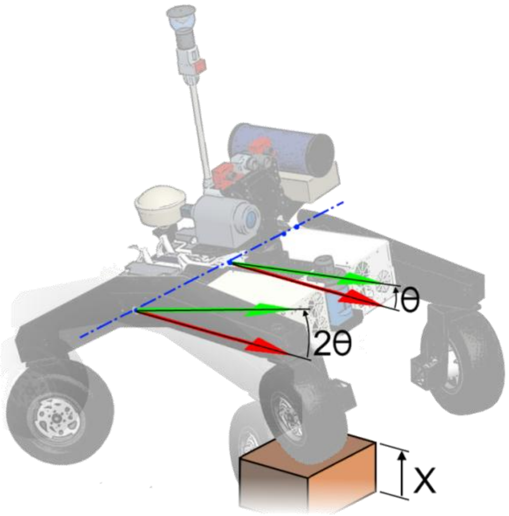


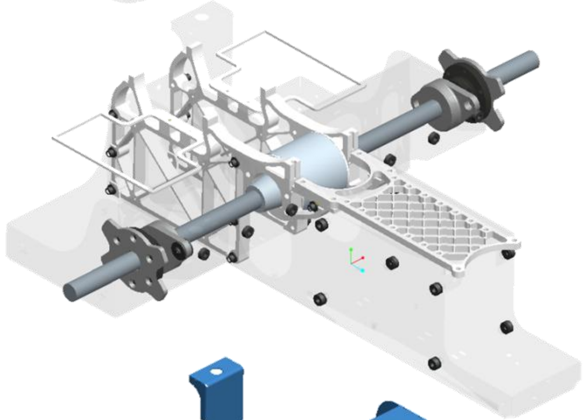
Mechanical

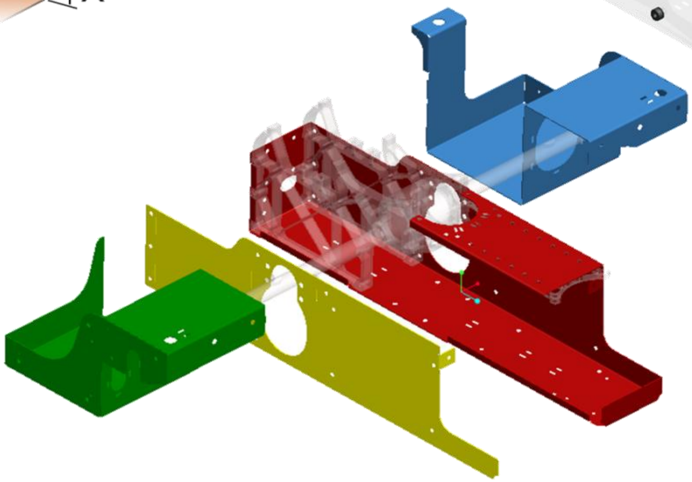
Mechanical
(Chassis)

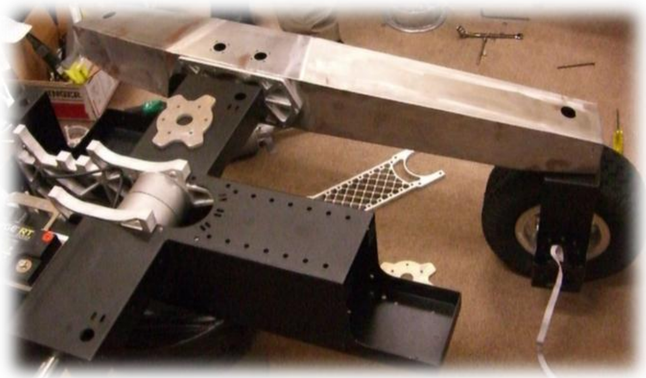
- Kinematic differential suspension
- Equipment (batteries and sensor devices)
- CG adjust with variable Pan-Tilt mounting



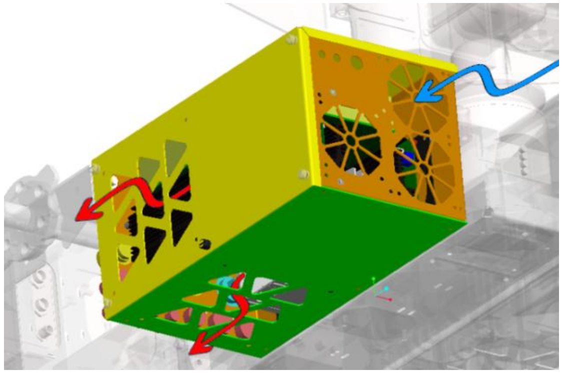




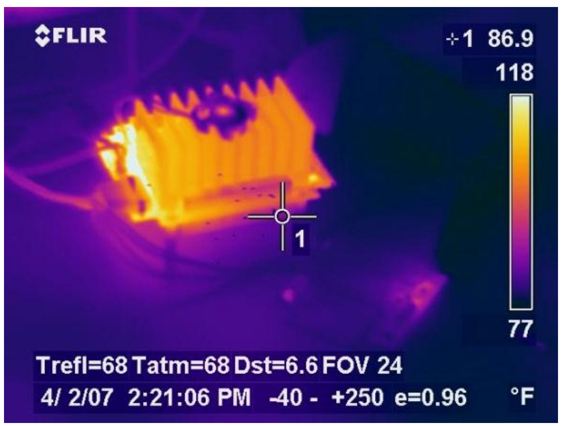


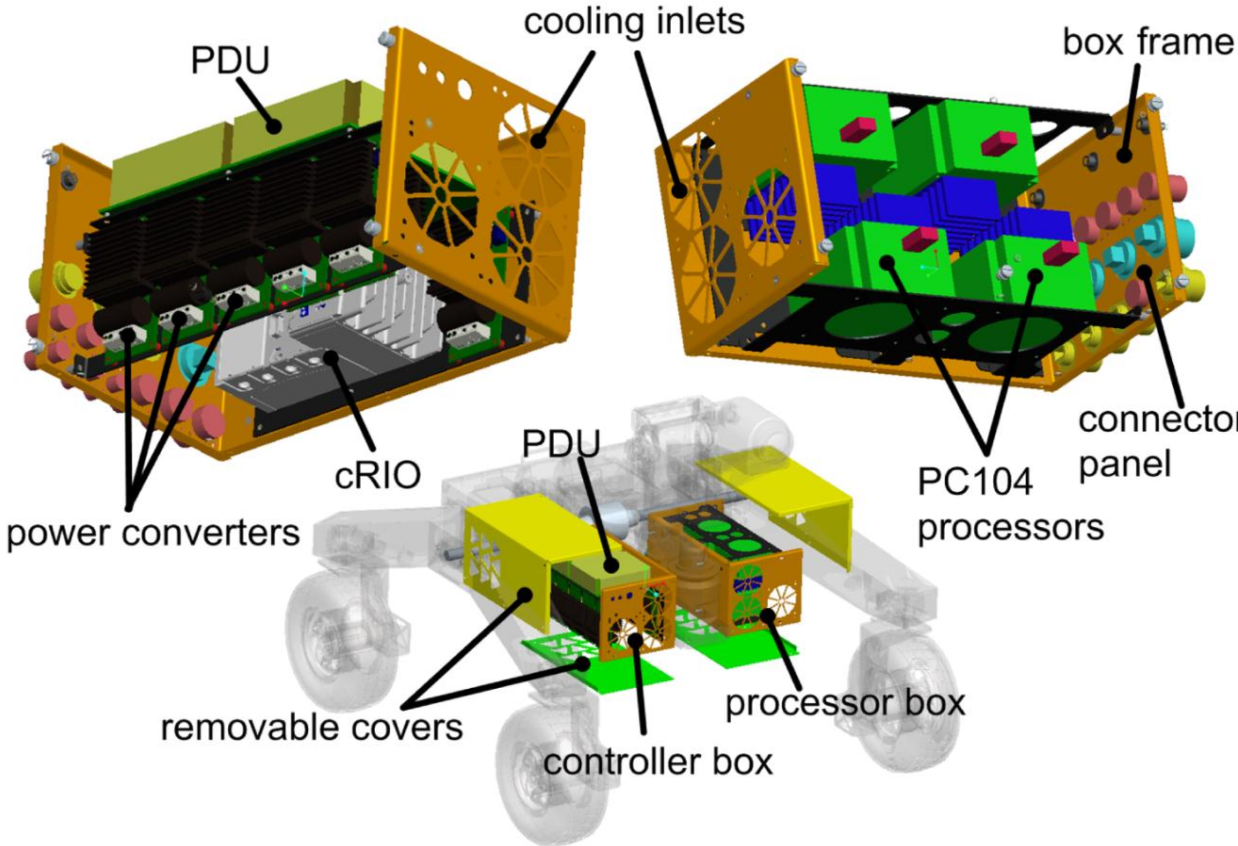


Mechanical
(Enclosures)



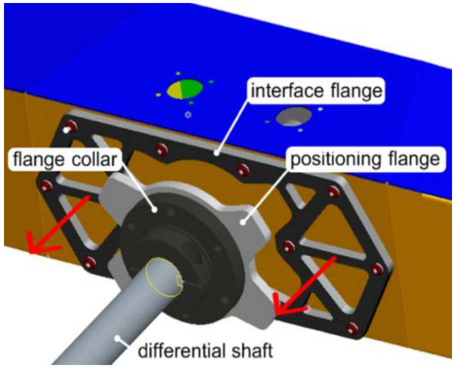
- Forced convective cooling
- Removable
- Three-side easy access
- Separate system controller and processing enclosures

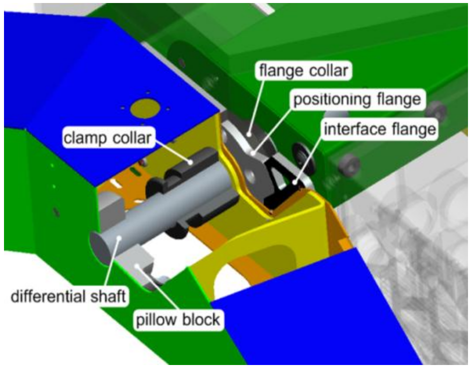


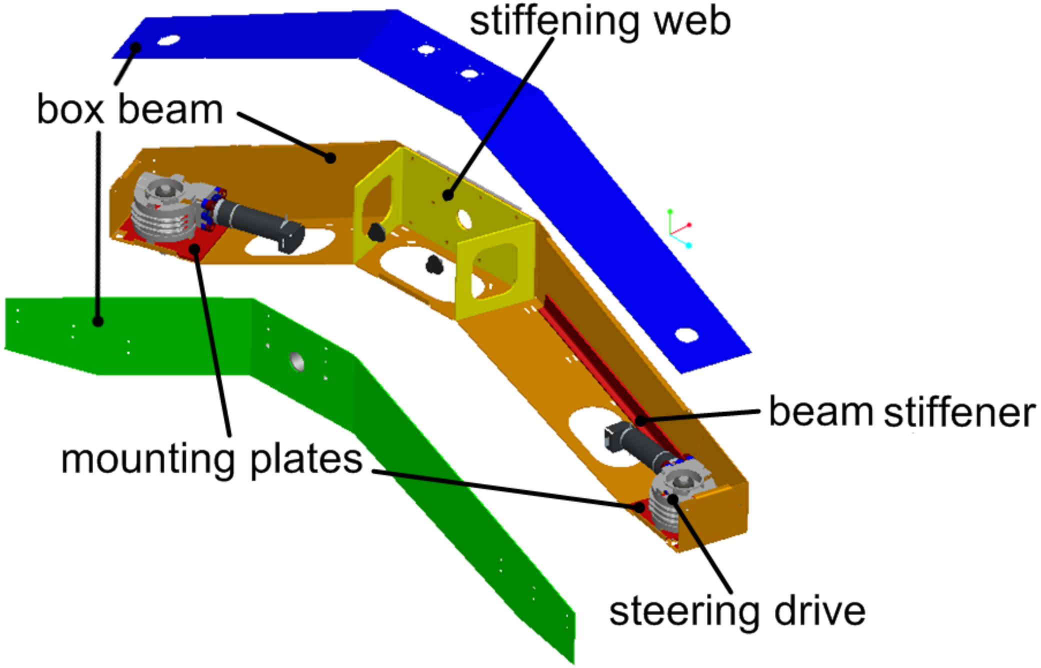


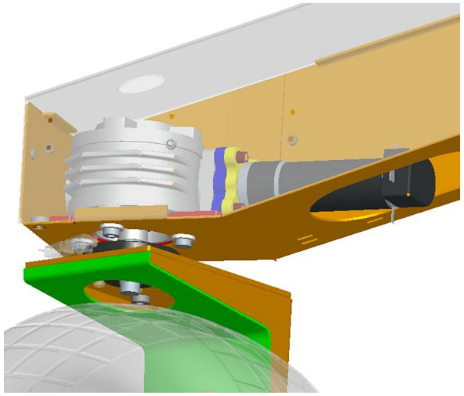
Mechanical
(Rocker-Arms)

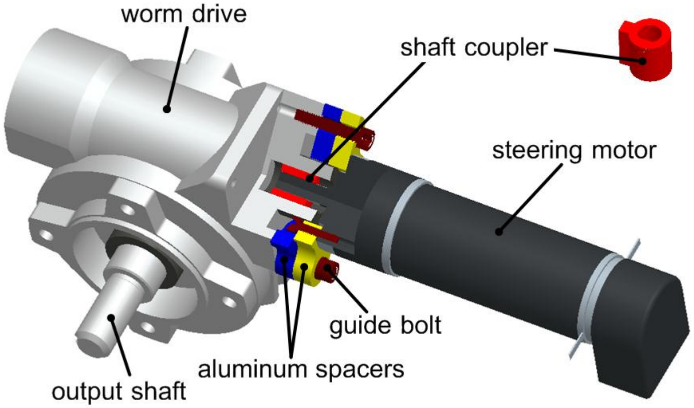
- Removable non-planar rocker-arm design
- Light-weight box beam
- Enclosed wheel position drive

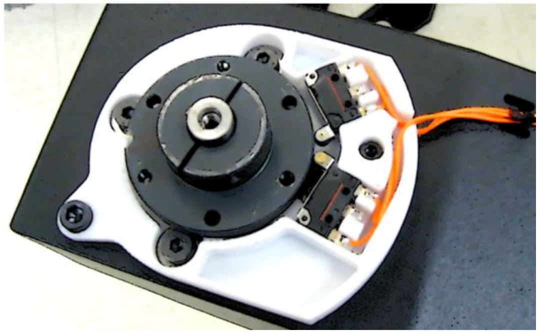






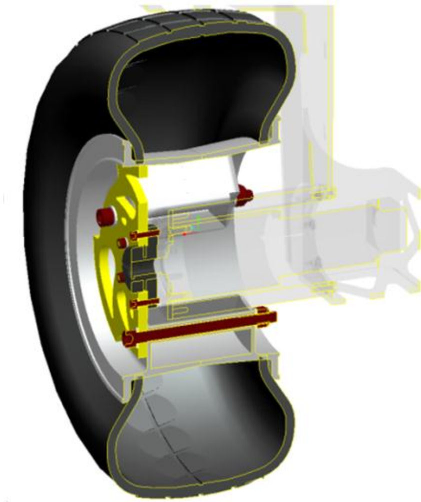


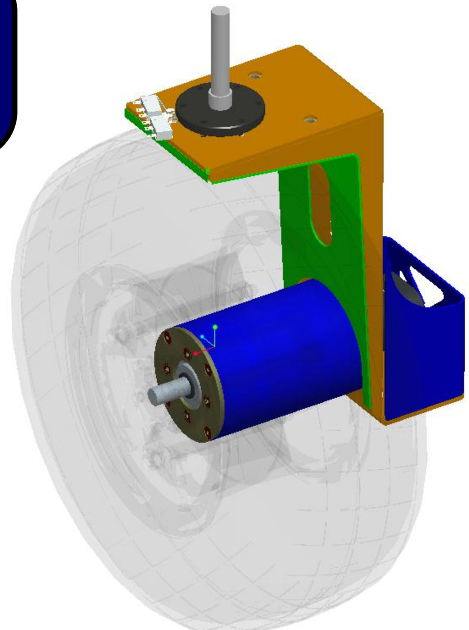


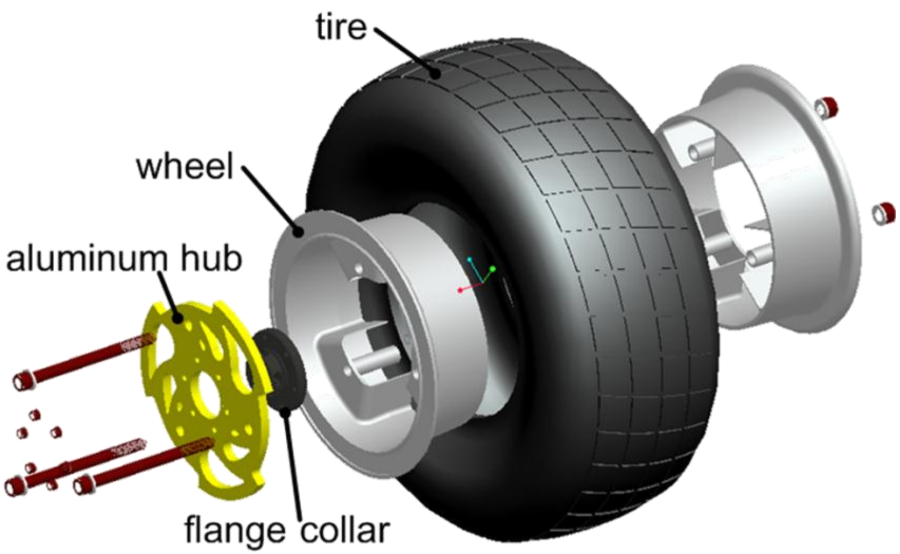


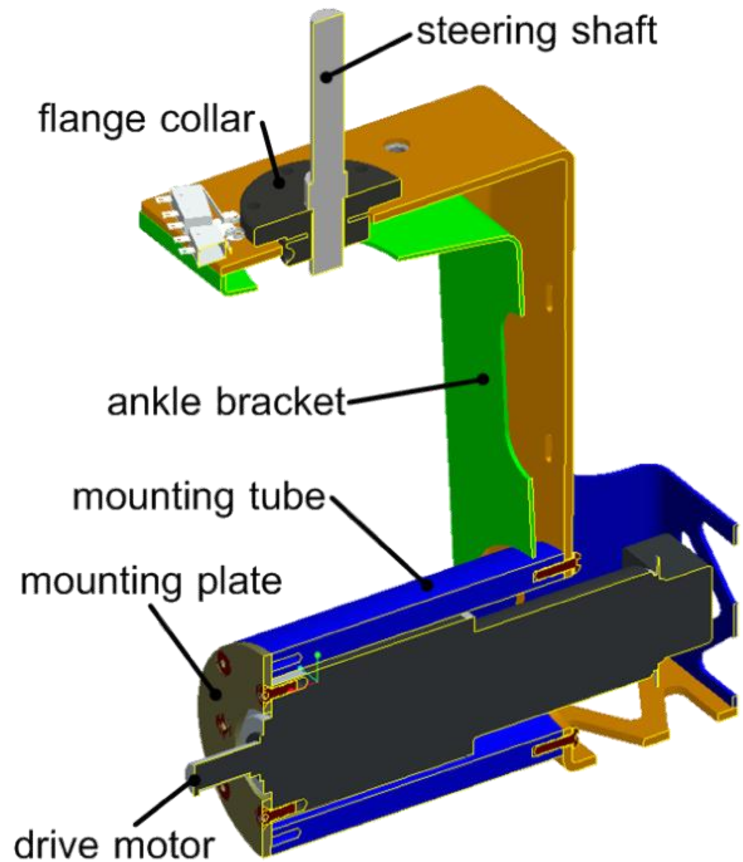
Mechanical
(Wheel/Ankle)

- Zero offset caster
- Motor-in-wheel design
- Concentrate design intensity to custom bracket
- Design to COTS wheel

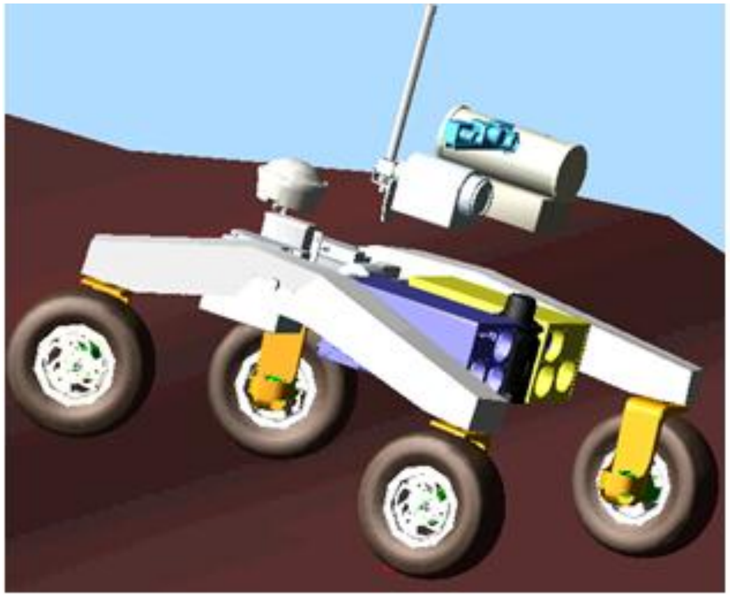


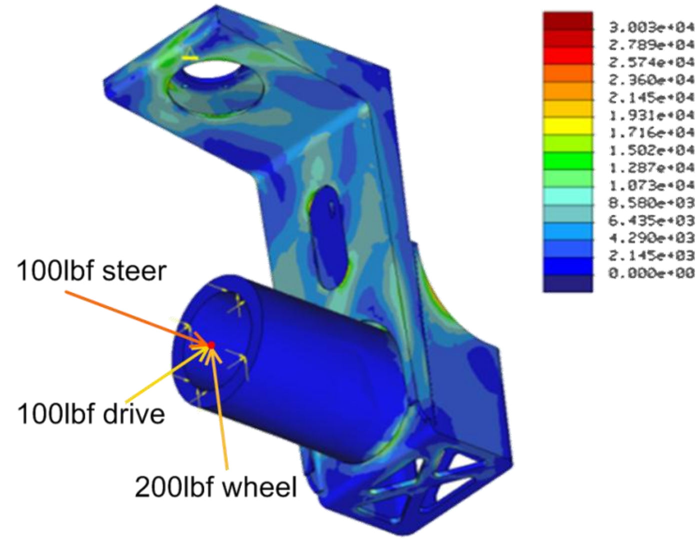


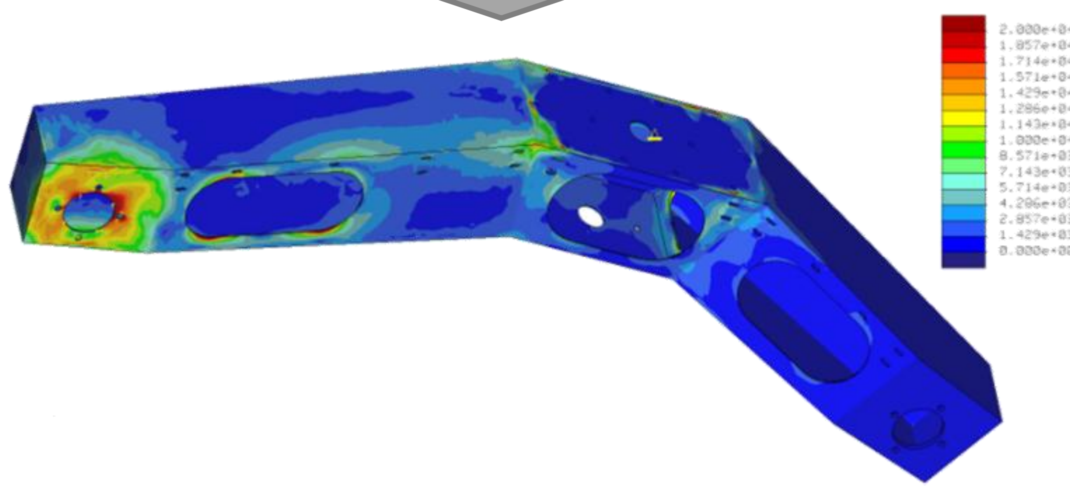




Mechanical
(Simulation and Analysis)



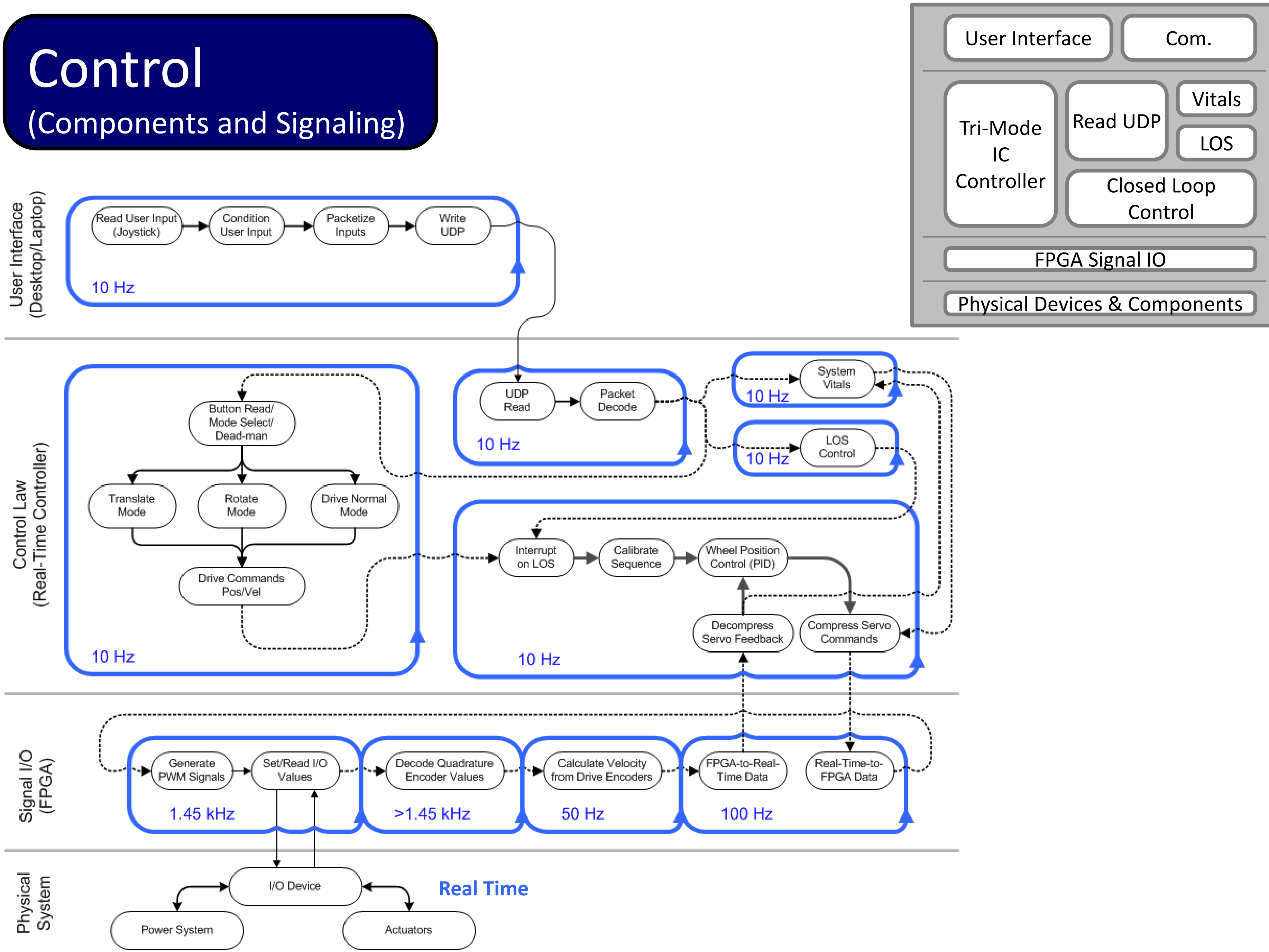




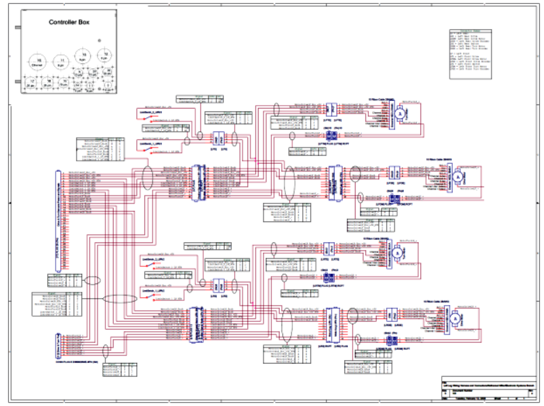
- Model vehicle
- Generate loads by simulation
- Analyze ankle
- Translate loads and analyze rocker arm (forward beam)

Control Implementation
Control by Instant Centers

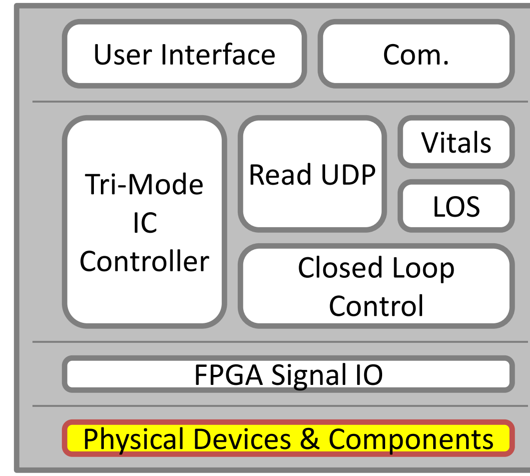
Control
(Components and Signaling)

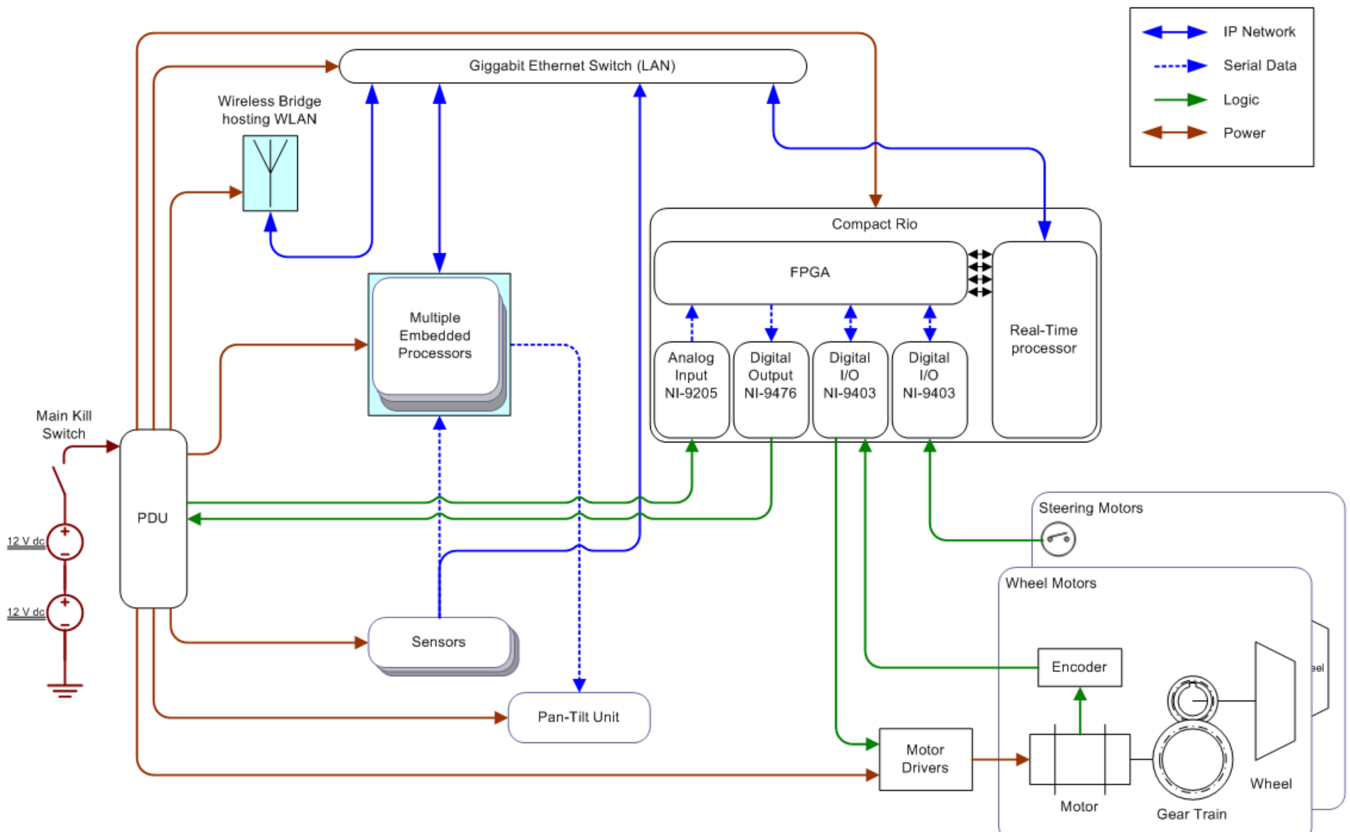


Control
(Physical System)

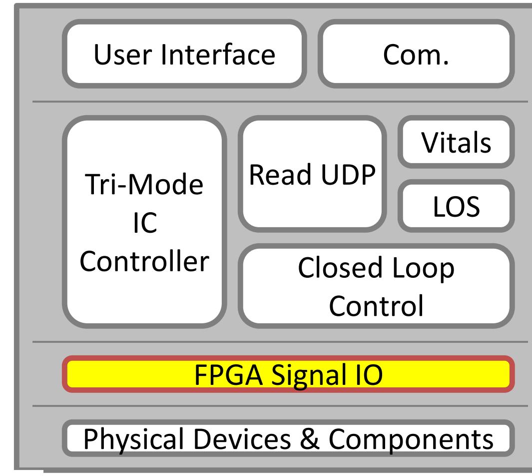


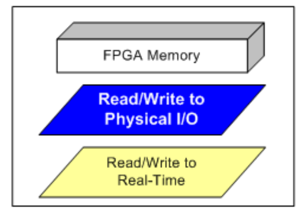
Sample Wiring Diagram

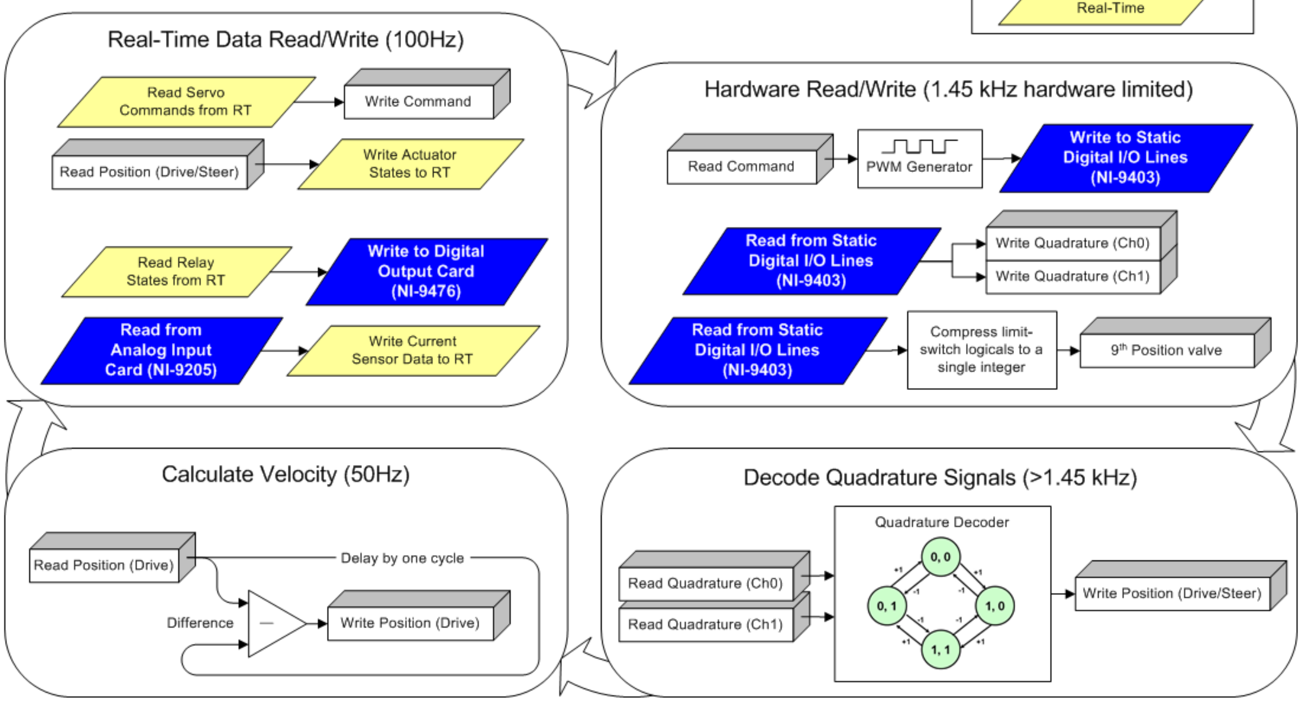




Control
(FPGA Digital Design)

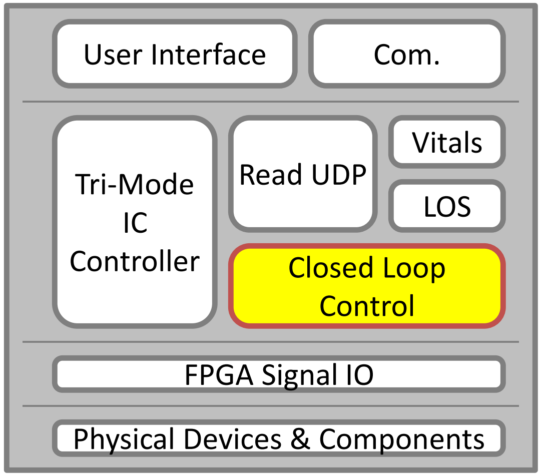


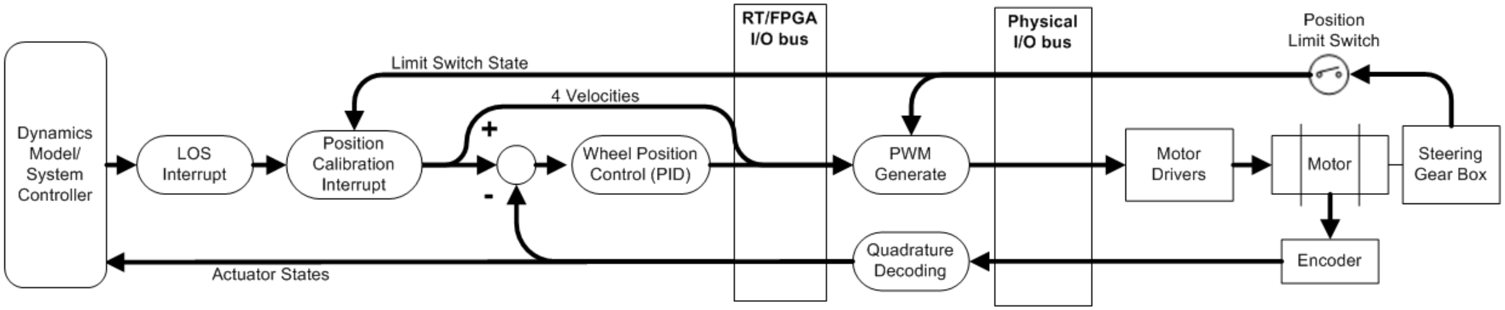


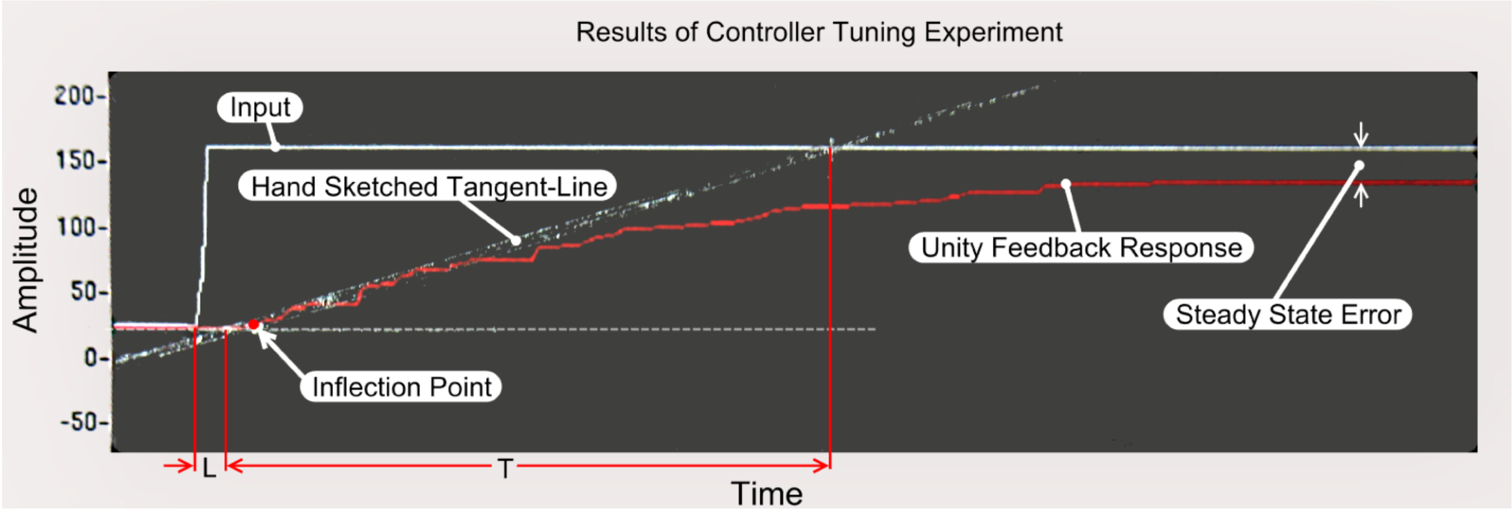


Control

(Closed-Loop Servo Control)

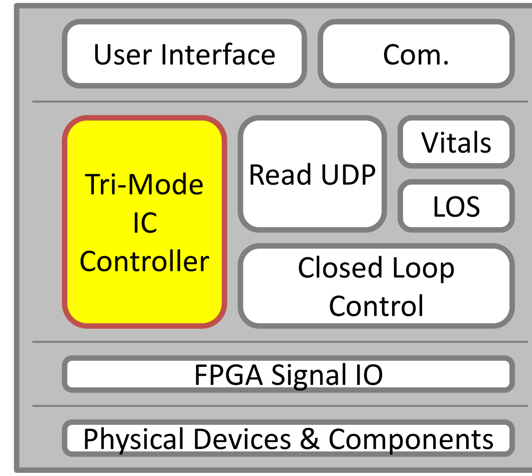






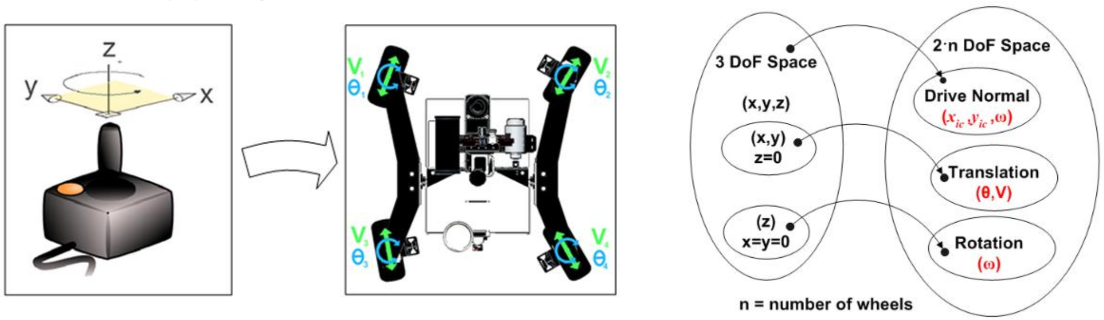
Control by Instant Centers

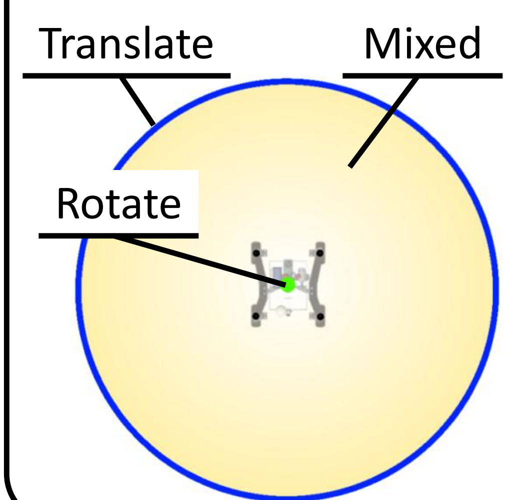
(The IC-Plane)



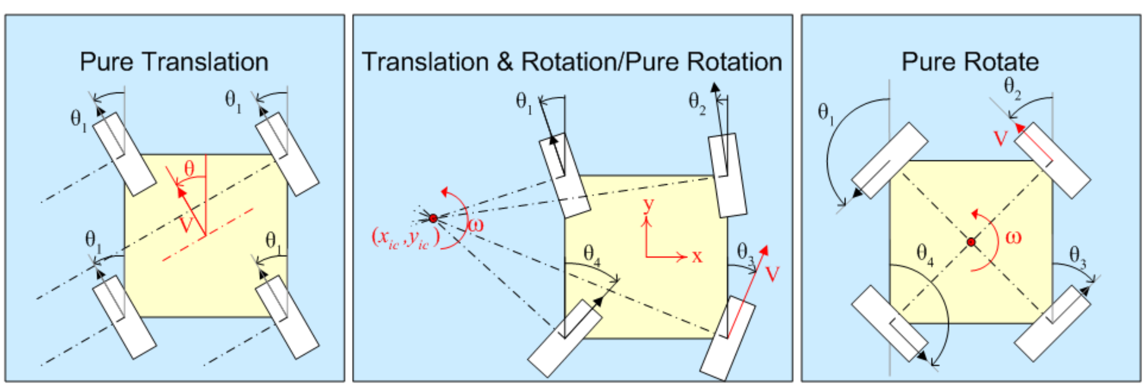
- Mapping problem
- The IC-Plane is a vehicle centric geometric interpretation of the three classes of planar motion

The Mapping Problem





Classes Of Drivable States



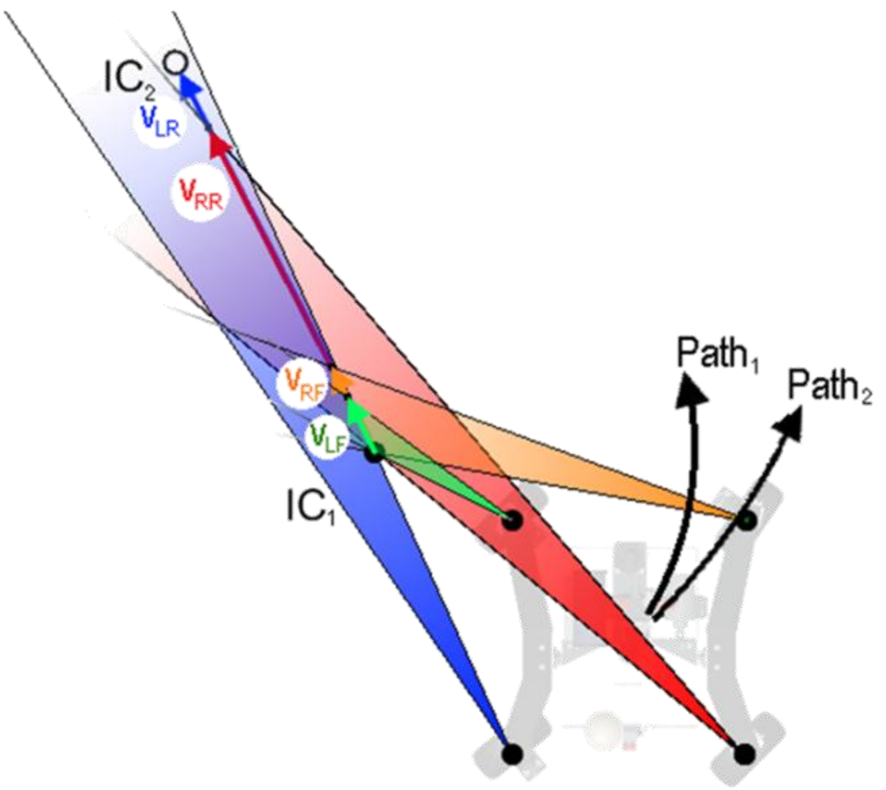
- Drivable State: The wheel positions and velocity conform to the constraints of planar motion

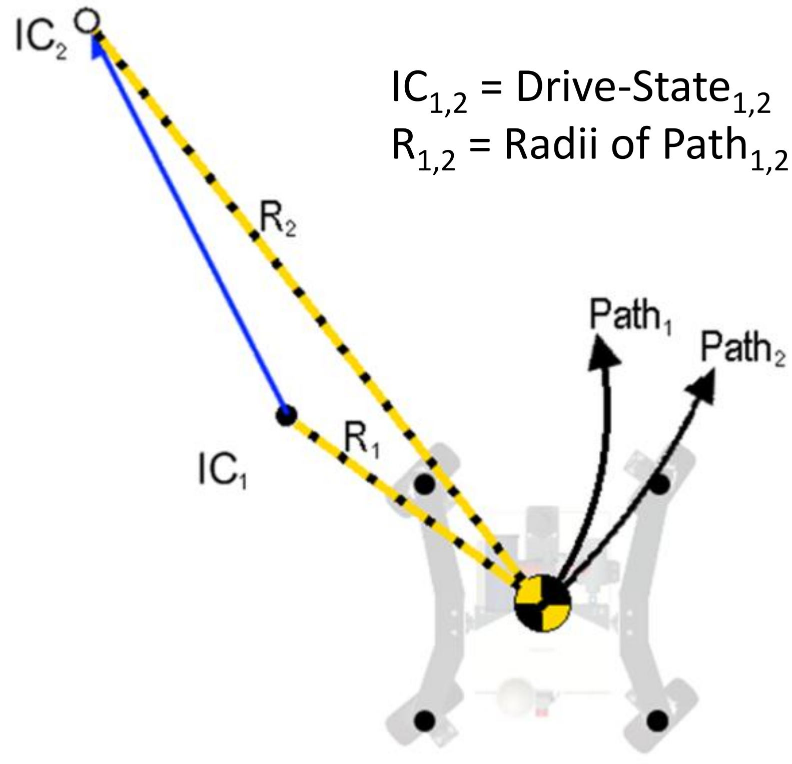
Control by Instant Centers

(The Notion of the IC-Path)

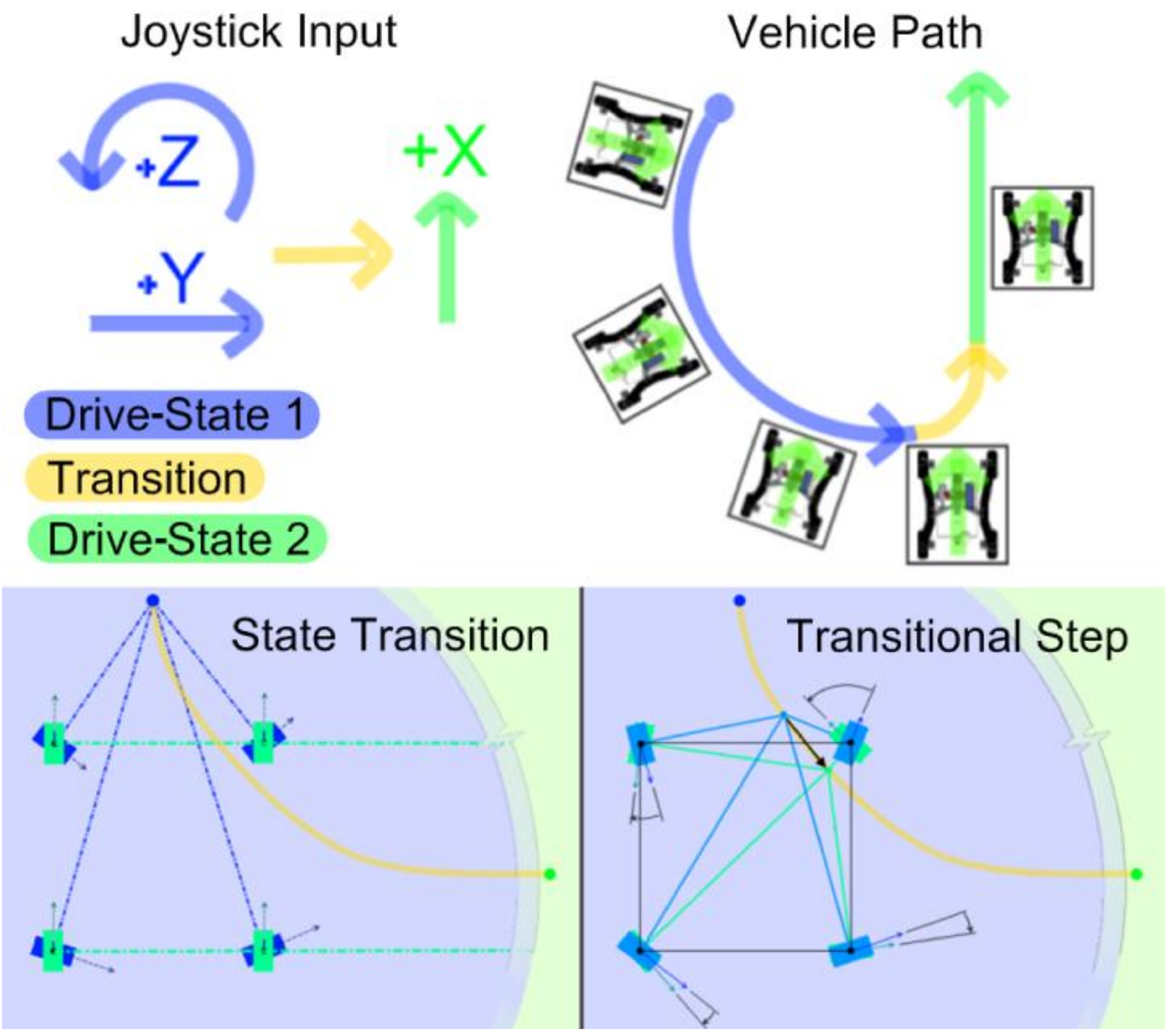
- IC-Path implies time dependence
- Actuator slew rate defines a ‘one-step region’

- The one-step region relates the physical constraints of the system to the IC-Path in the geometric IC-Plane
- Every IC-Step on the IC-Path must reside in the overlap of all one-step regions





Control by Instant Centers
(The General Problem)

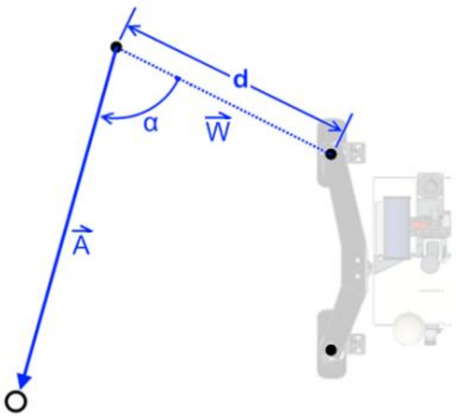


- Abstract part of the global path-planning problem into a structured context
- Both the drivable state and the IC-Path are redundantly satisfied by the mobility base

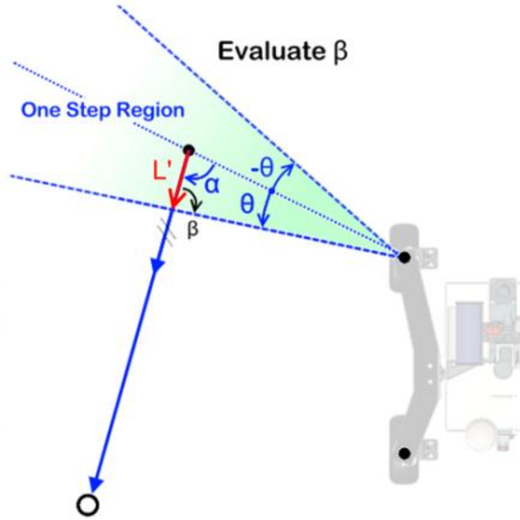
Control by Instant Centers

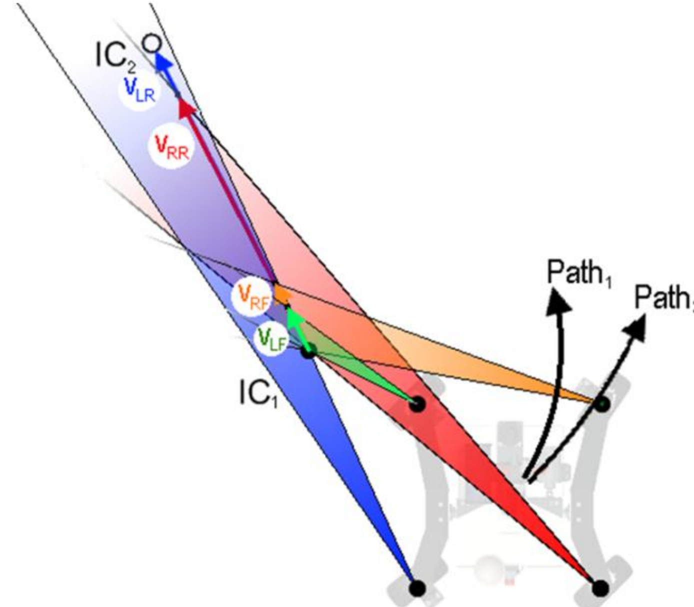
(Geometric State Control for the IC-Path)

Calculate d and α



Evaluate β

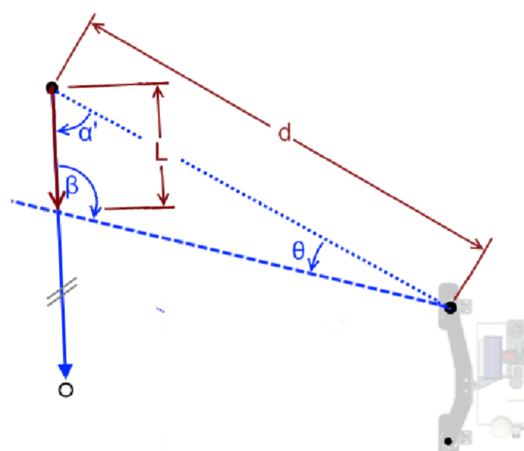


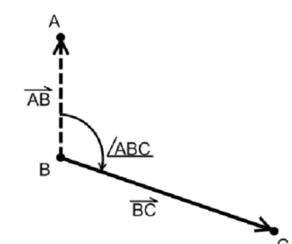


$$\alpha = \left(\frac{\vec{W} \times \vec{A}}{\left| \vec{W} \times \vec{A} \right|} \right) \cdot \cos^{-1}\left(\frac{\vec{W} \bullet \vec{A}}{\left| \vec{W} \right| \cdot \left| \vec{A} \right|} \right)$$

$$\frac{\sin\beta}{d} = \frac{\sin\theta}{L'}$$

$$L = \left| \frac{d \cdot \sin\theta}{\sin\beta} \right|$$



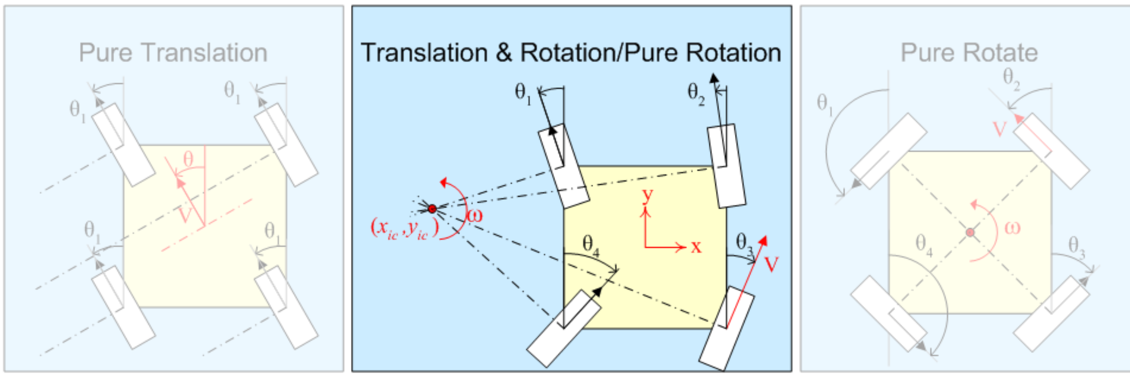


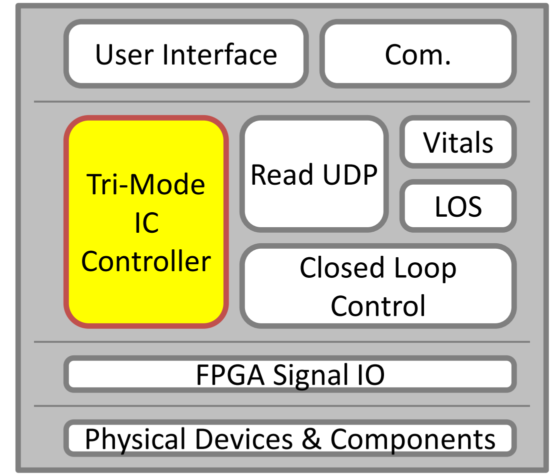
$$\overrightarrow{BA} \bullet \overrightarrow{BC} = \left|\overrightarrow{BA}\right| \cdot \left|\overrightarrow{BC}\right| \cdot \cos(\angle ABC)$$

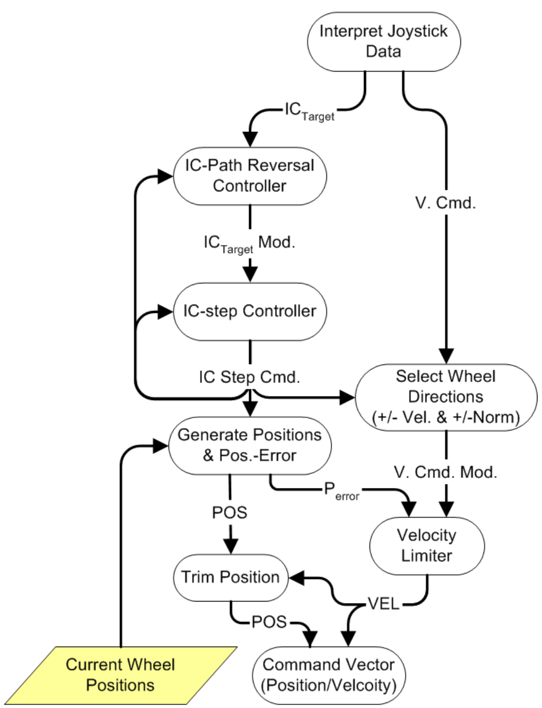
$$\angle ABC = u \cdot \cos^{-1}\left(\frac{\overrightarrow{BA} \bullet \overrightarrow{BC}}{\left|\overrightarrow{BA}\right| \cdot \left|\overrightarrow{BC}\right|} \right)$$

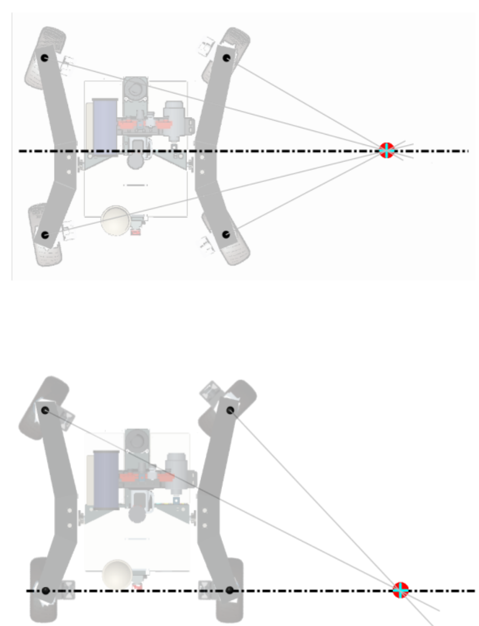
Where $u = \frac{\overrightarrow{BA} \times \overrightarrow{BC}}{\left|\overrightarrow{BA} \times \overrightarrow{BC}\right|}$

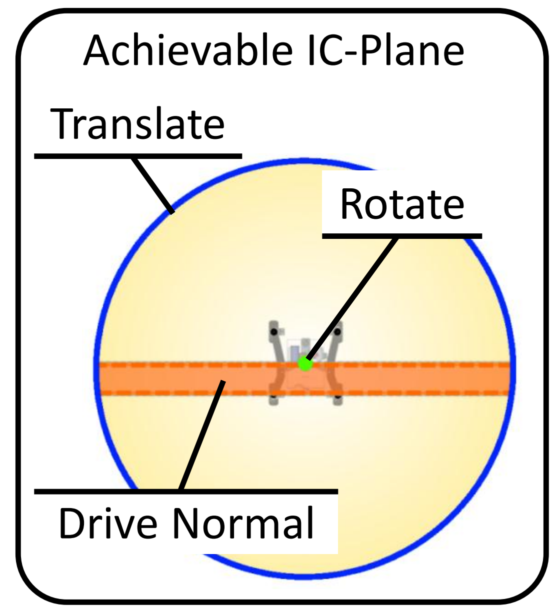
Drive Normal Mode
(Control Scheme)





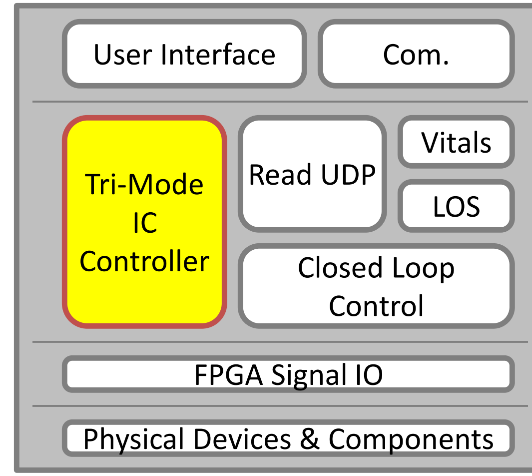


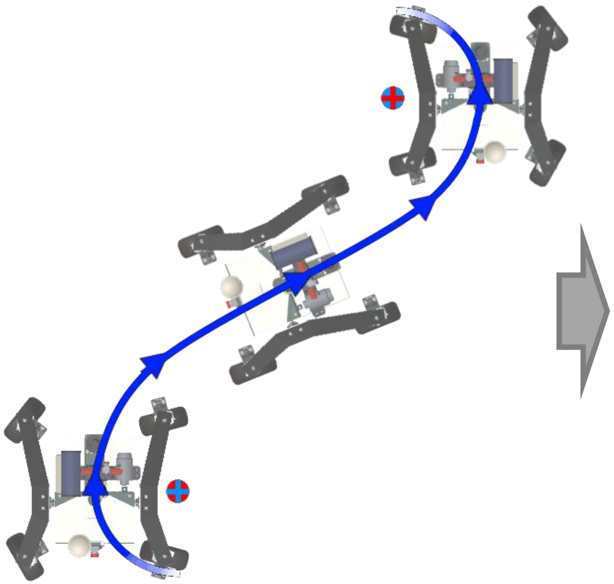


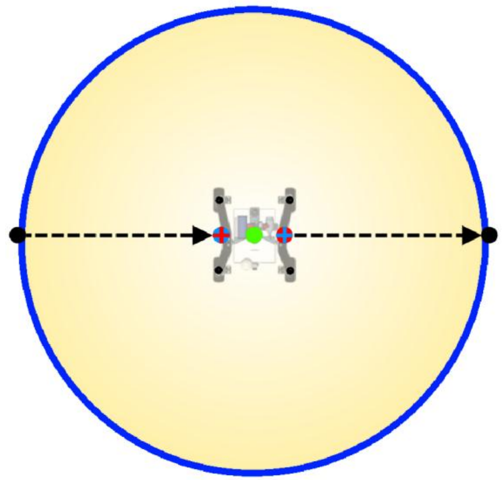


- Intuitive operation
- Steerage ratio
- Steering limit

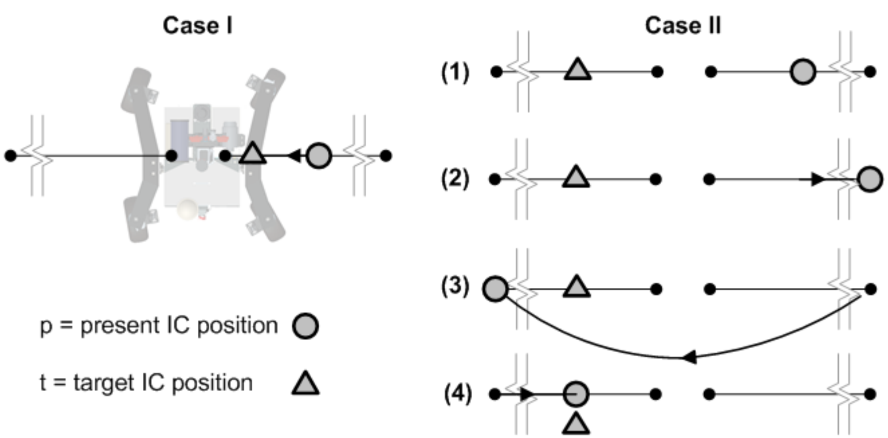
Drive Normal Mode
(IC-Path Planning)

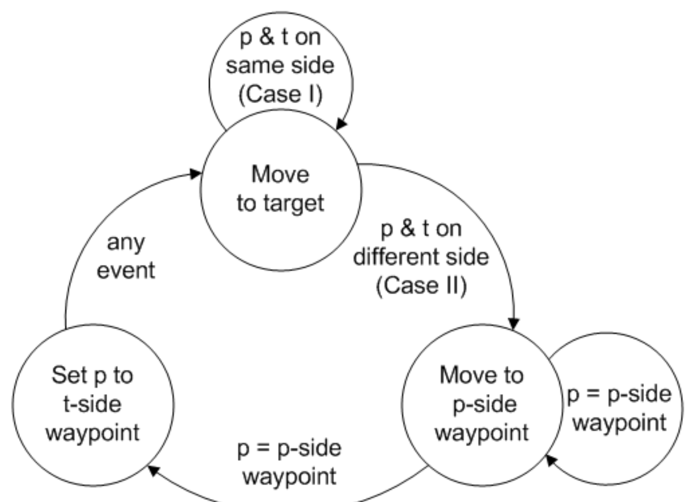






- Map global vehicle path to IC-Path
- Path planning algorithm/behavior





Drive Normal Mode

(Velocity and Trimming)

- IC-Plane to actuator commands requires velocity control and trimming

Velocity

- Velocity magnitude defined by the ratio of IC radii
- Maximum angular wheel position error limits velocity command
- Limit is imposed with a weighting function

Trim

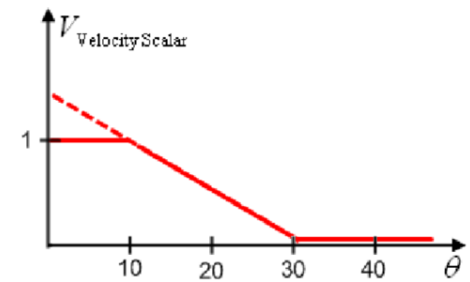
- Mechanical slop leaves the system unrivaled without trim compensation
- Use programmatic toe-in to take advantage non-uniform torsional rigidity of box beam

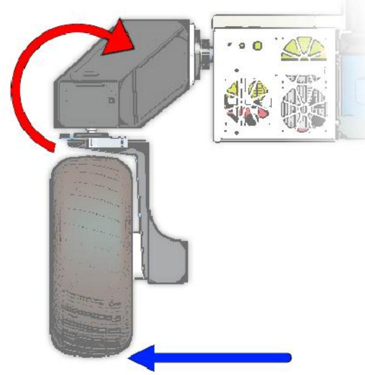
Velocity Magnitude Coefficients

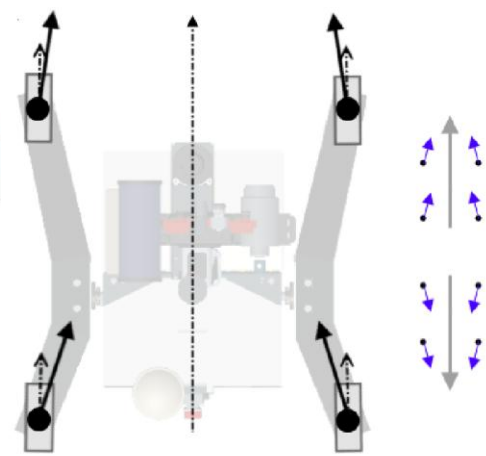
$$\vec{c_v} = \frac{\overrightarrow{R_{IC}}}{R_{IC-\max}}$$

Velocity Limiting

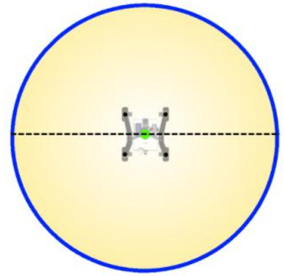
$$V_{\text{VelocityScalar}} = \begin{cases} 1 & , e < 10^\circ \\ \dfrac{4-\theta}{3} & , 10^\circ \le e \le 30^\circ \\ 0 & , e \ge 30^\circ \end{cases}$$

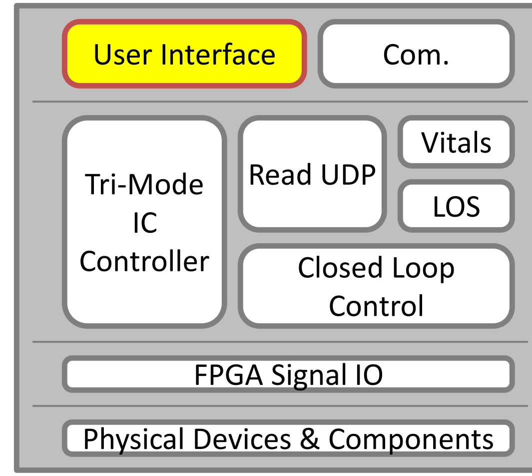




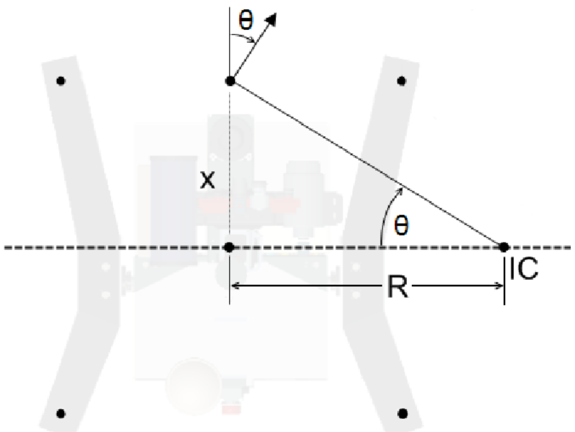


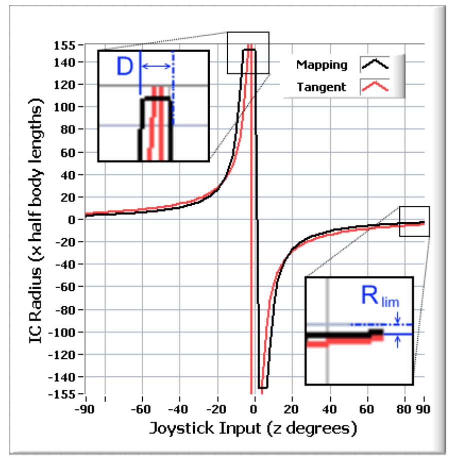
Drive Normal Mode
(User Input Mapping)





$$R_{IC} = \frac{x}{\tan(b \cdot \theta)} \qquad R_{cmd} = \min(150, R)$$

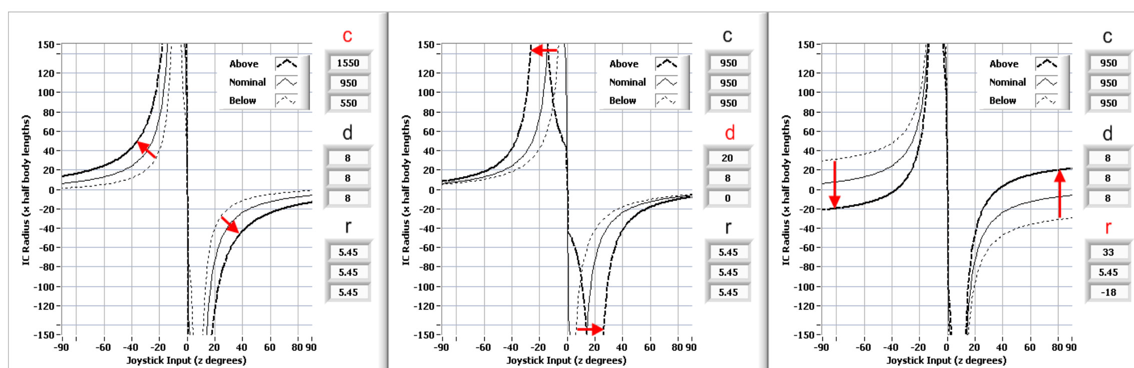




- Steer from an ‘imaginary wheel’
- Adjustable input mapping
- Tuned with vehicle in the loop

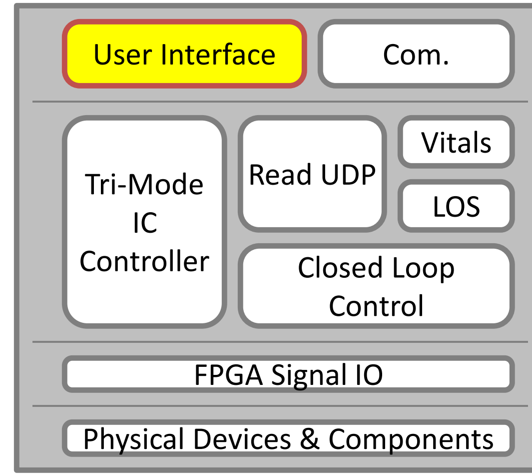
$$R_{IC} = \left(\left|\frac{c}{|z_{joy}| - d}\right| - r\right)\frac{z_{joy}}{|z_{joy}|}$$

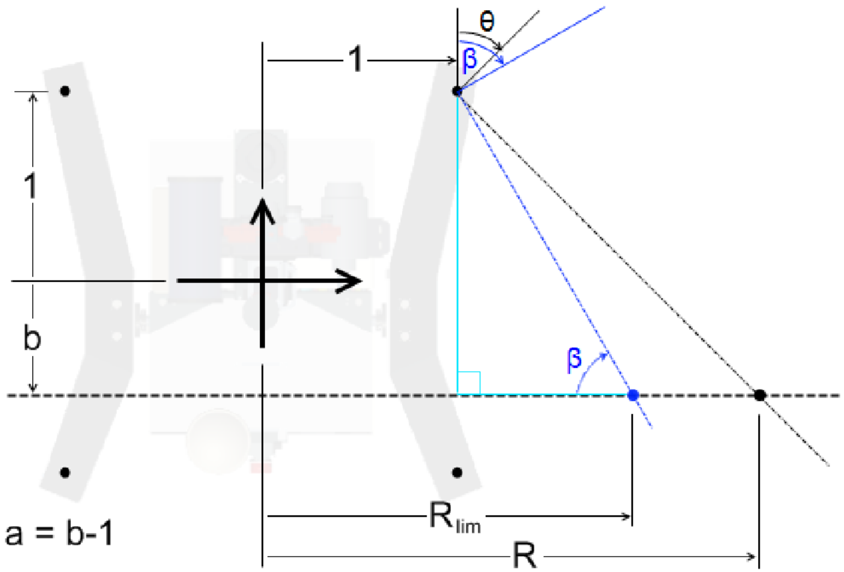
$$R_{cmd} = \min\left[150, \left(\left|\frac{950}{|z_{joy}| - 8}\right| - 5.45\right)\frac{z_{joy}}{|z_{joy}|}\right]$$



Drive Normal Mode

(Input manipulation)



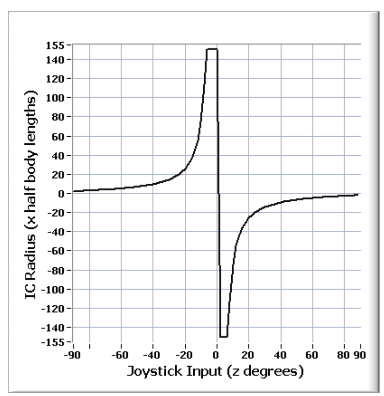


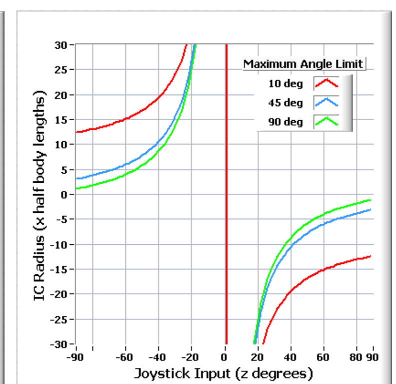
- Steerage ratio *b*
- Steering limit *β*
- Restrictions on the accessible range of the IC plane.

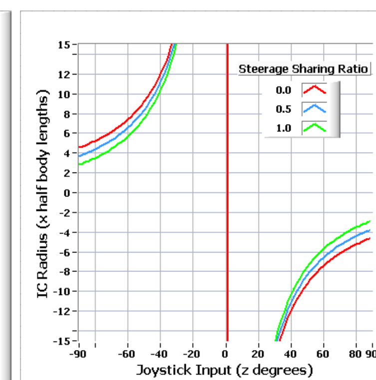
$$\tan(\beta) = \frac{1+a}{R_{\lim} - 1}$$

$$R_{\lim} = \frac{1+a}{\tan(\beta)}$$

$$R_{IC} = R_{cmd} + R_{cmd}\left(R_{\lim} \cdot \frac{150 - |R_{cmd}|}{150 \cdot |R_{cmd}|}\right)$$



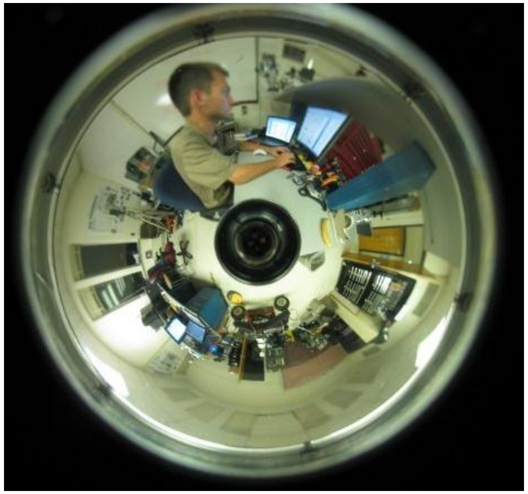




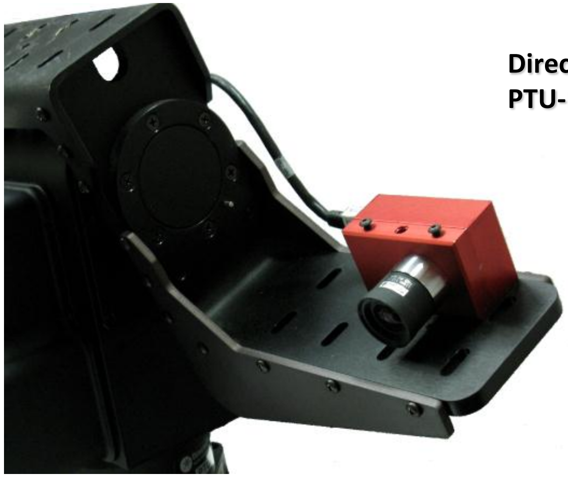
Sensor Implementation

Sensors
(Implemented Devices)

Directed Perception PTU-D300 Pan-Tilt



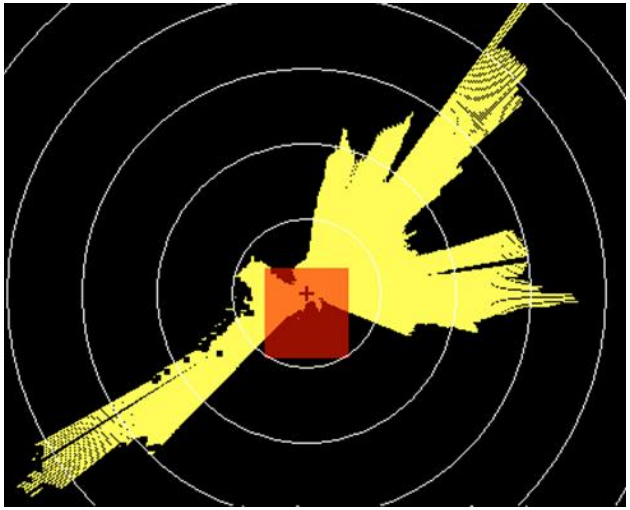
Soios 55 Omnidirectional Lens



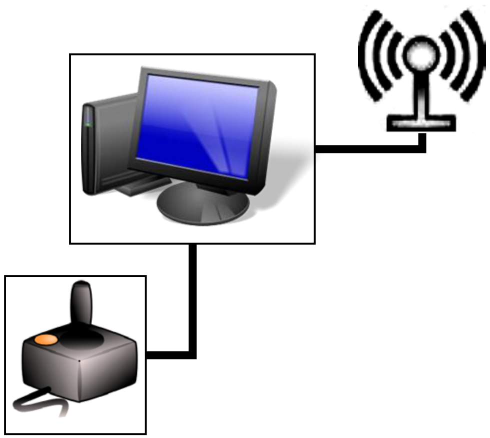
Videre DCSG CCD imager

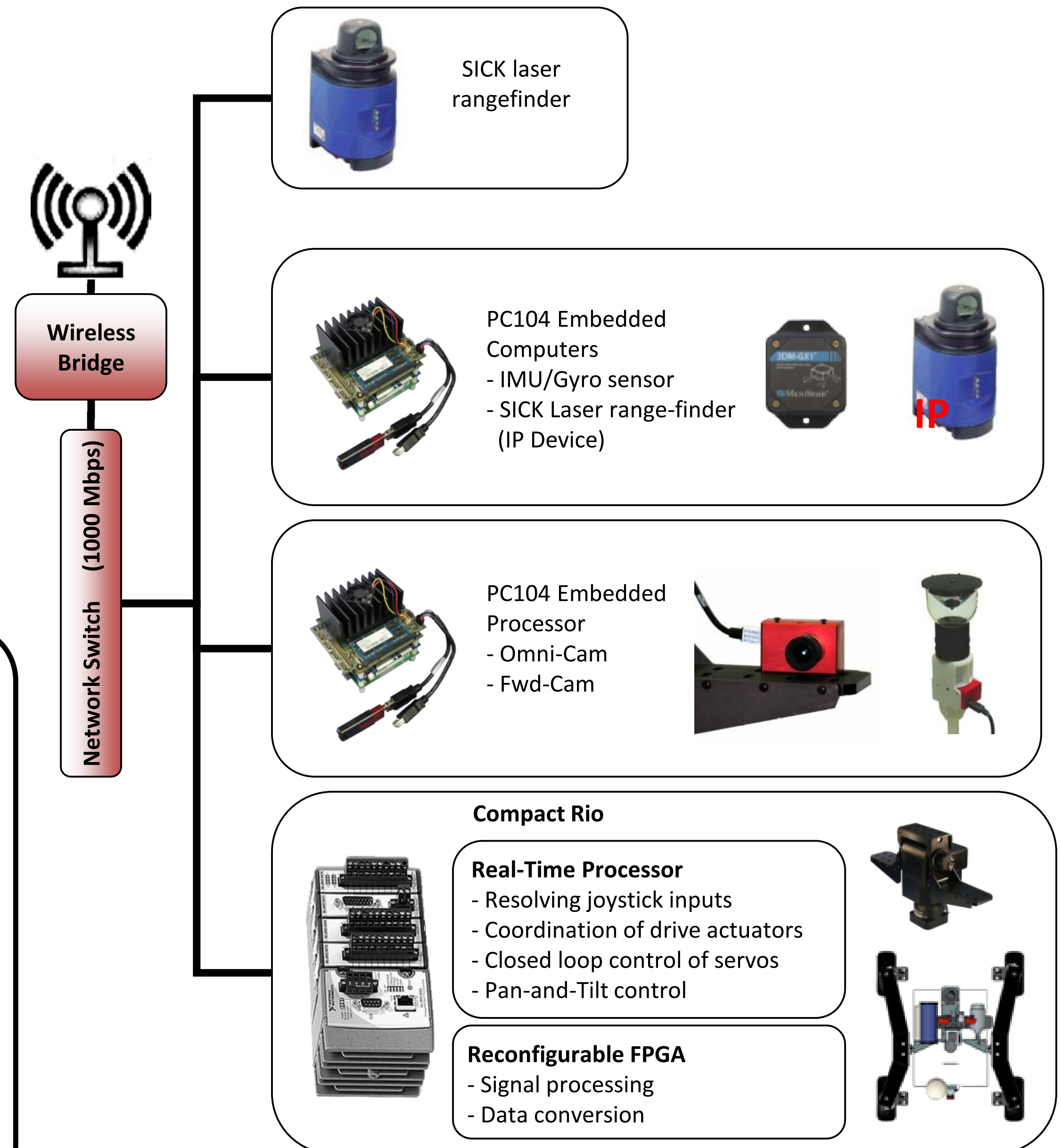
MicroStrain 3DM-GX1 IMU Gyroscope

SICK LD-OEM1000 Laser Range Finder



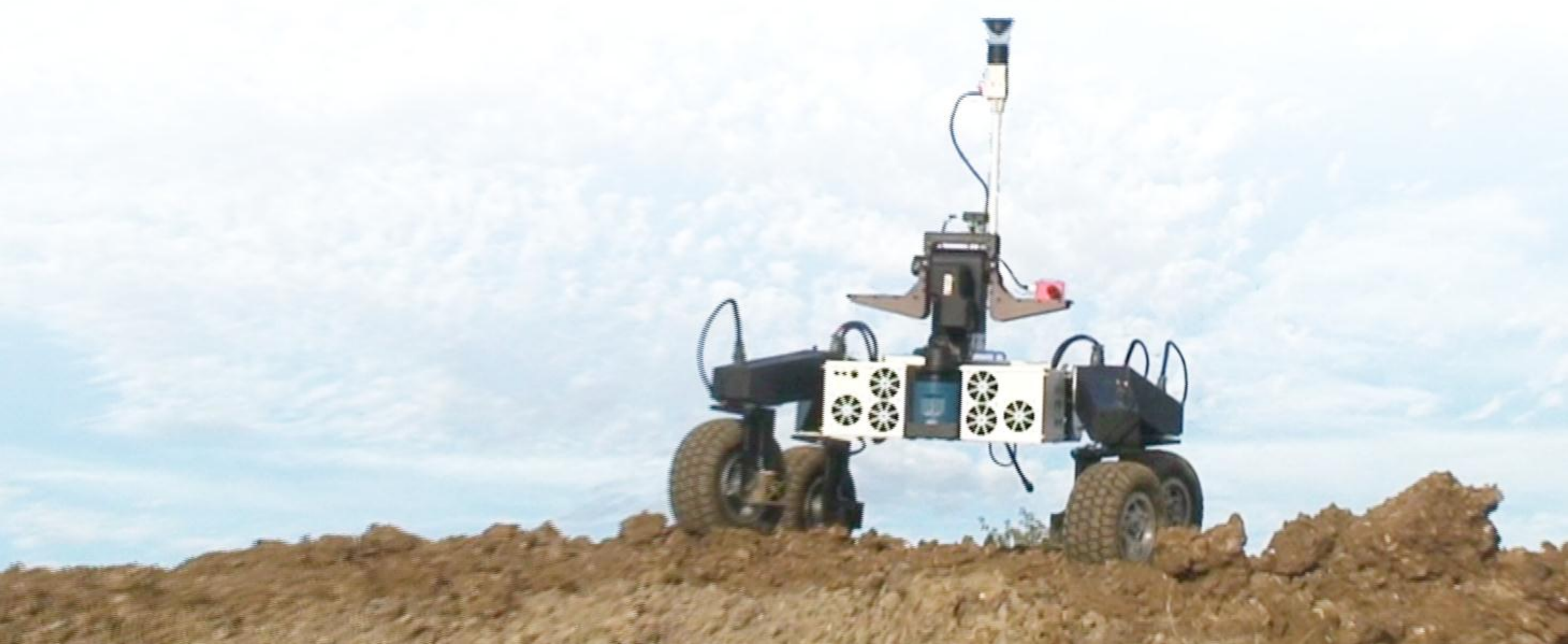
Sensors
(Implemented System)





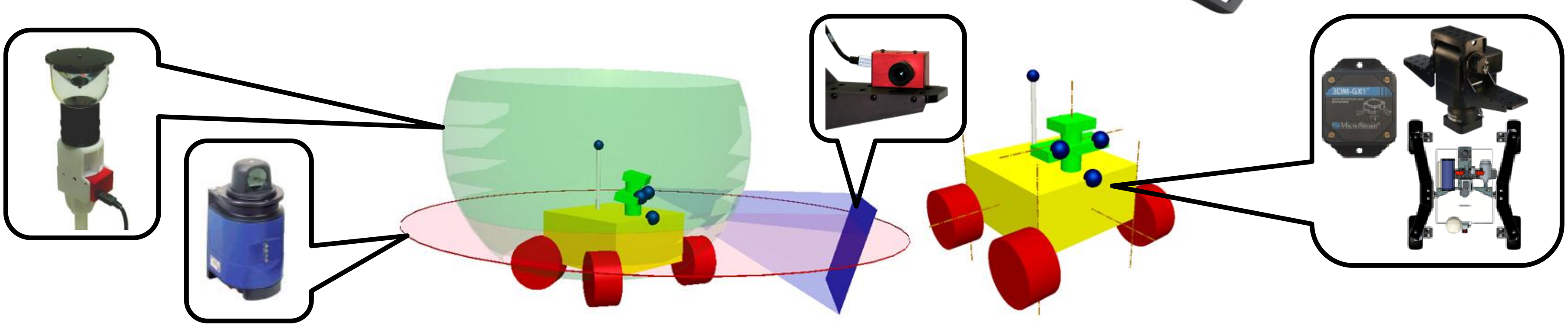
- IP Networked
- Embedded XP + LabVIEW
- Windows remote desktop
- Network-shared variables for all sensor data
- TDMA using LV sequence structure
- UDP for all actuator command and control

User Interface

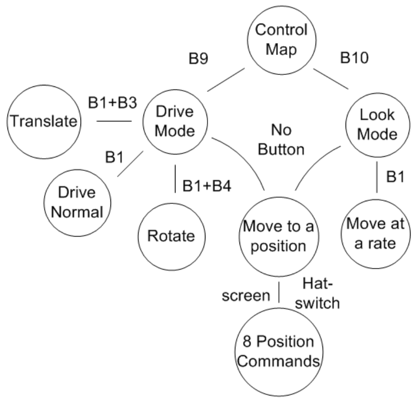


User Interface
(Sensor Data)

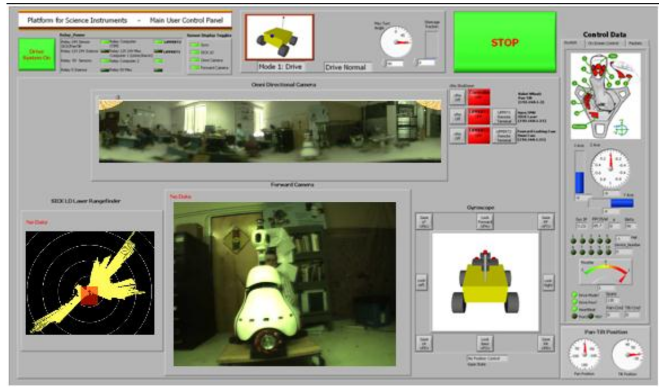
- Perspective has an effect on use of the mobile system (e.g., god's eye view vs. 1st person view)
- Layout modeled after an automotive dashboard
- User-directed gaze of forward camera

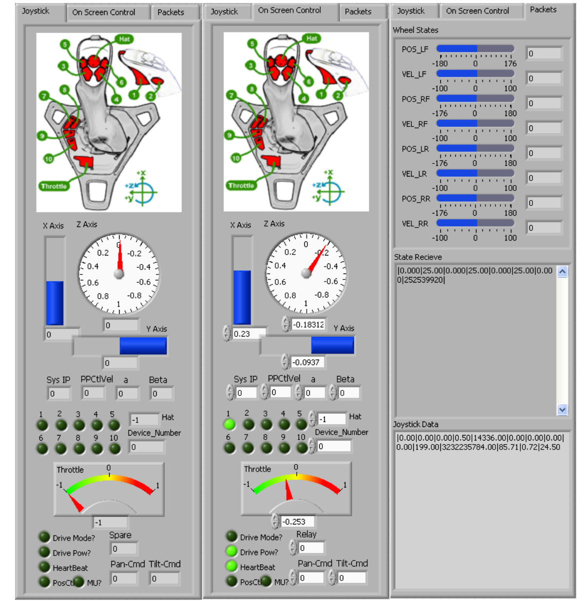


User Interface
(Command & Control)

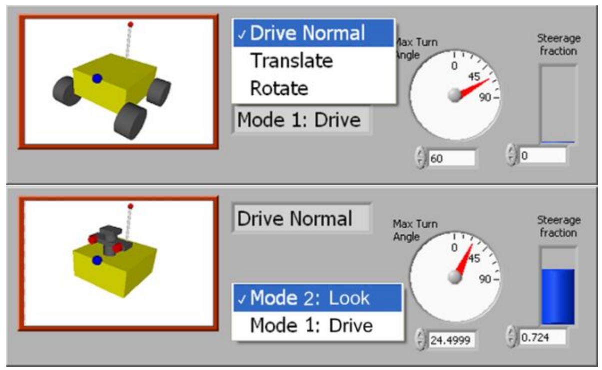


Input Mapping Selection Tree

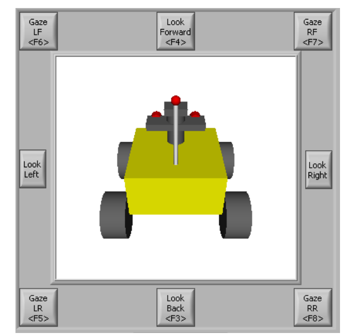




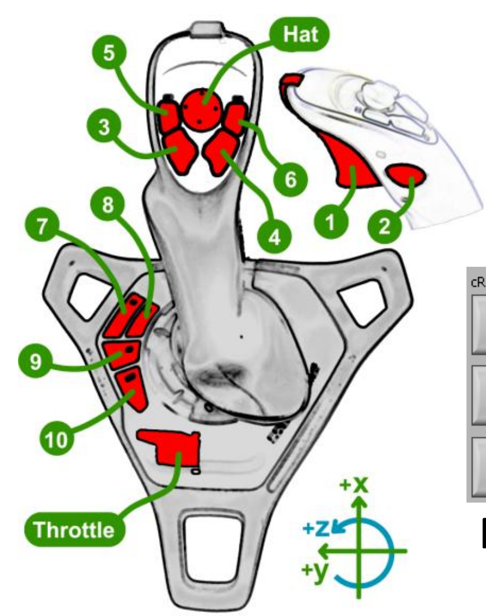
Com./Ctl. Access Panel



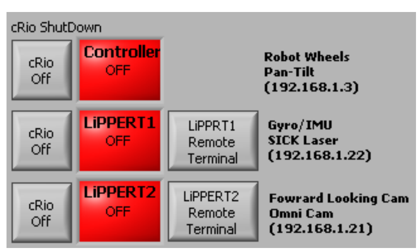
Input Mode Indicator



Onscreen Pan-Tilt Interface



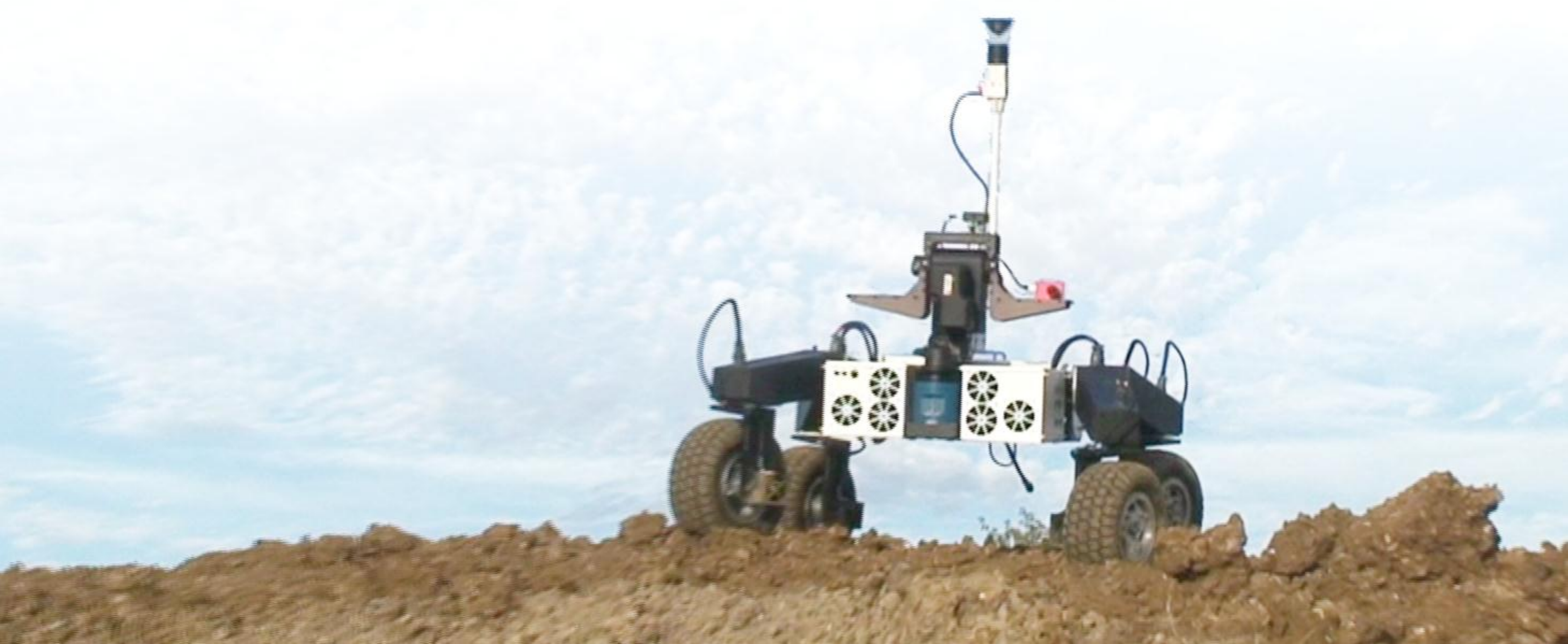
Joystick Input Definition



Processing Interface

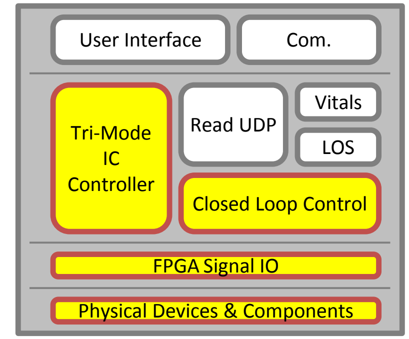
Power Distribution Unit (PDU) Interface

Results

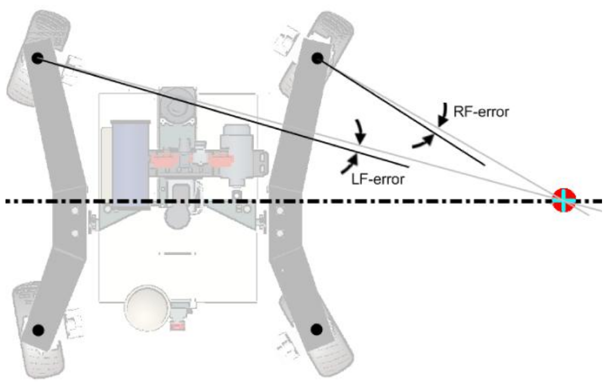


System Performance
(Actuation & IC controller)

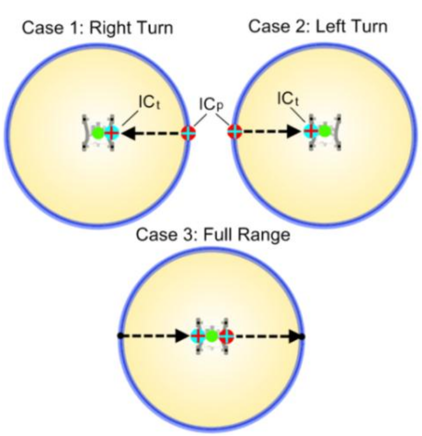
- IC state controller works
- Machine round-off error
- Possible lack of optimization



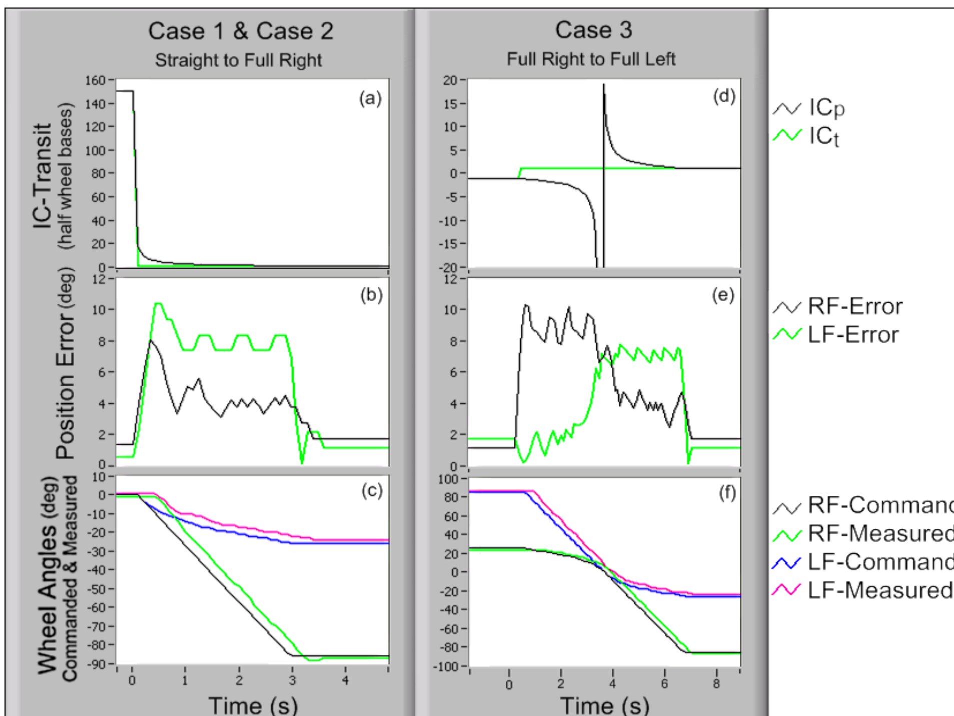
Components Under Examination

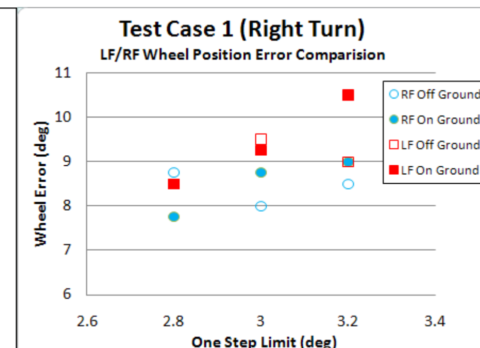


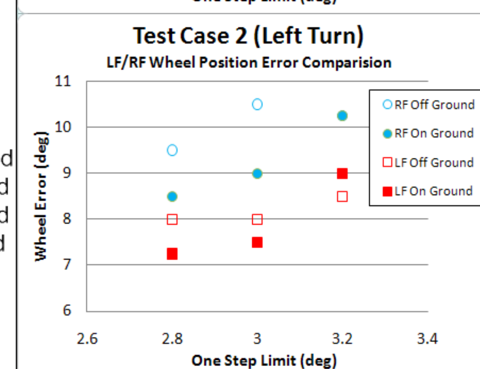
Error Measured



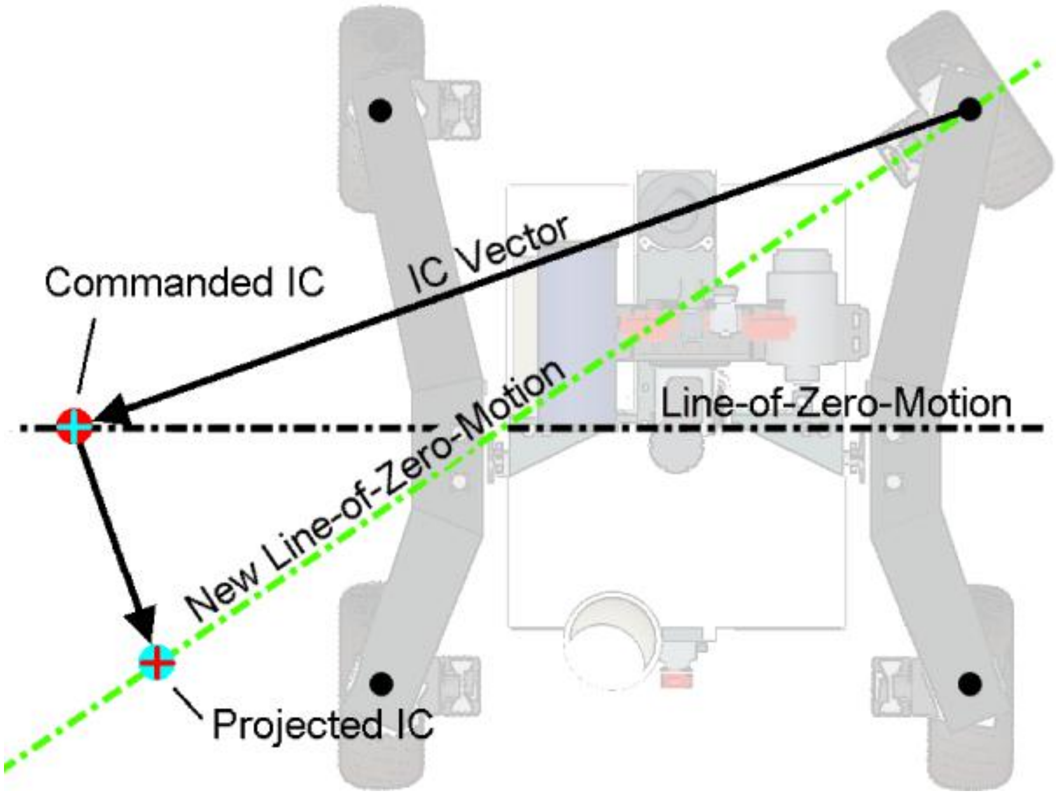
Tests Performed







System Performance
(Flexibility test for Instant Center Control)



- Fault tolerance implies modification to control system
- Test validates the system's behavioral attributes

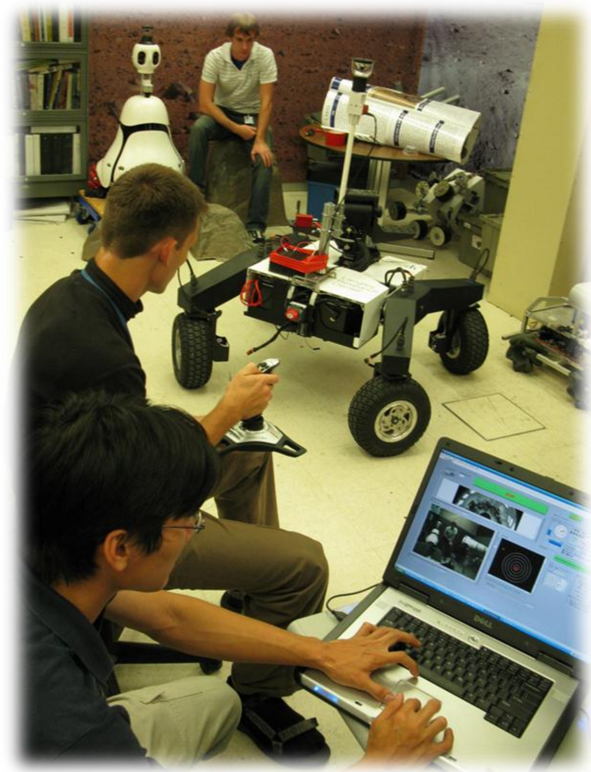
Method

- Failed wheel defines new line-of-zero motion
- Project command IC onto new line
- NO modification of user input
- No noticeable change in performance for failure angles up to 60°
- No difficulty in controlling system to failure angles of 90°
- Implementation time: <1 hour

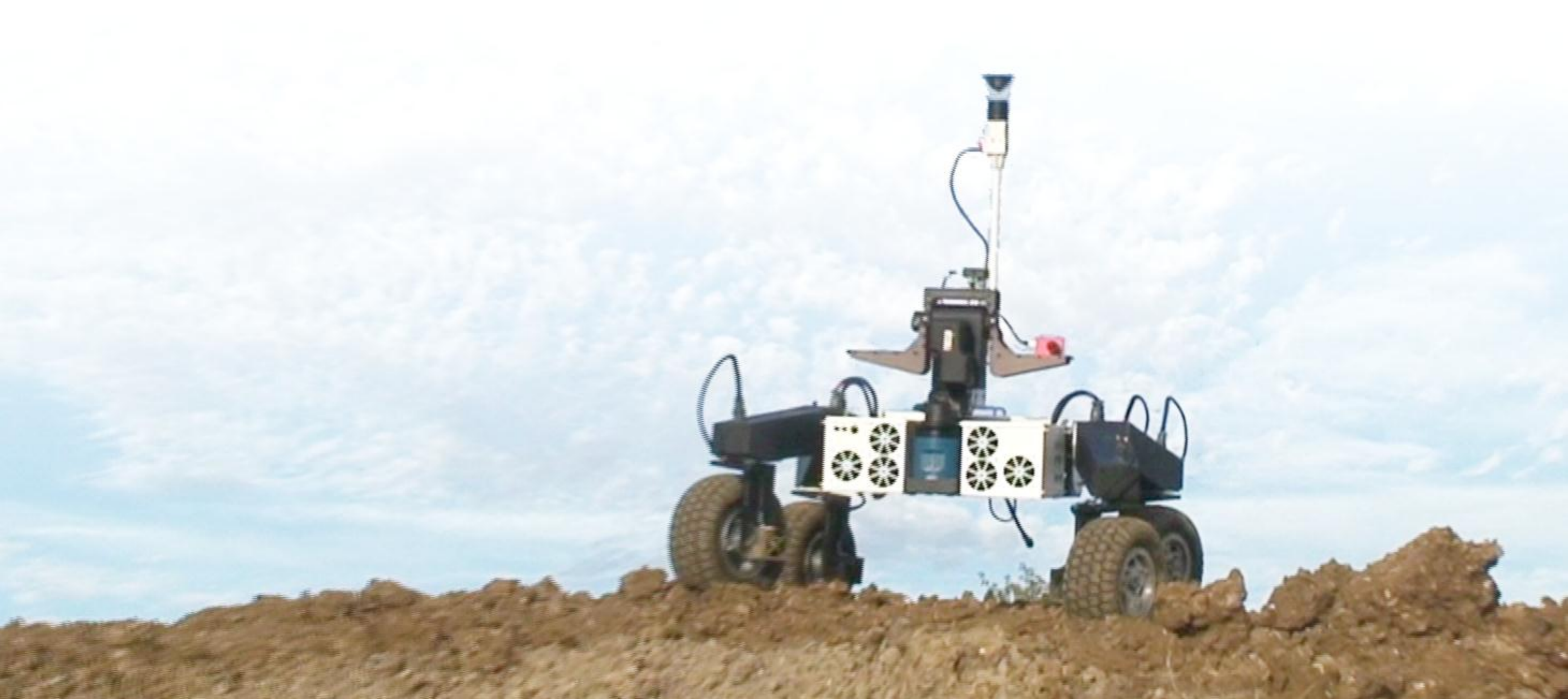
System Performance

(Vehicle Operation)

Maneuver	Condition	Measurement
Max ascent grade (experimental)	Grass slope	30°
	Loose dirt	29°
Max grade of decent & cross slope navigation	Validated	39°
	Theoretical	45°
Max right-angle step navigation	Direct approach (90°)	12 in
	Indirect approach (45°)	18 in
Max speed (any direction)	Flat & level ground	1.7 mph
Time to rotate 360° in place	—	0.8 s
Max steering transition time (full forward to full turn)	—	2.8 s
Time to pure rotation from full forward	—	1.1 s
Transition time between full forward and 90° lateral translation	—	2.8 s

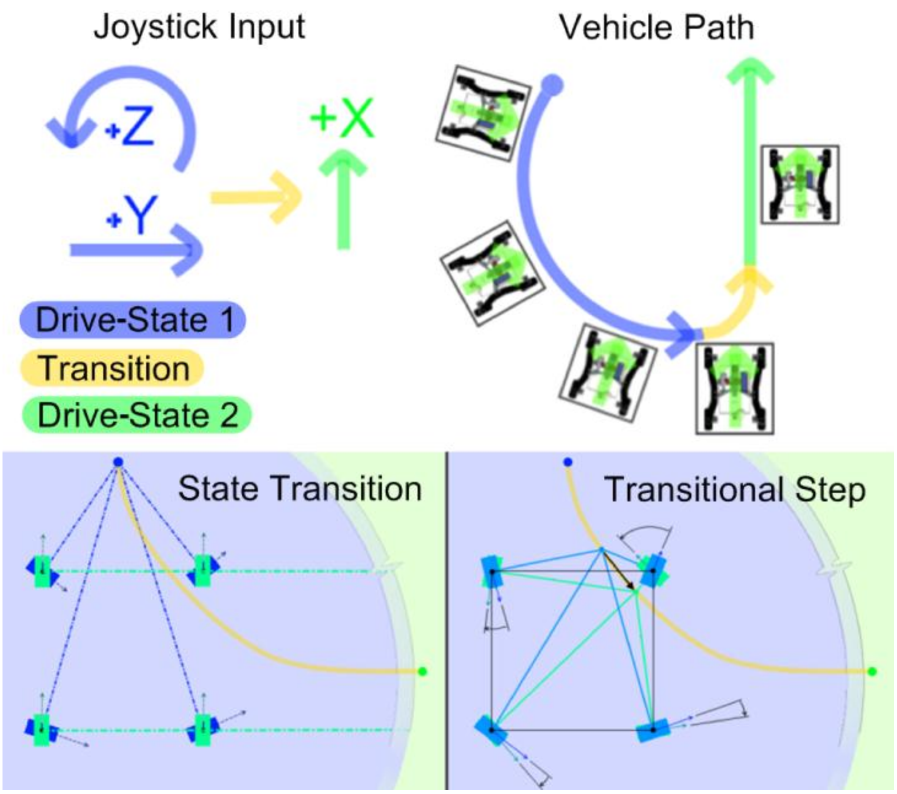


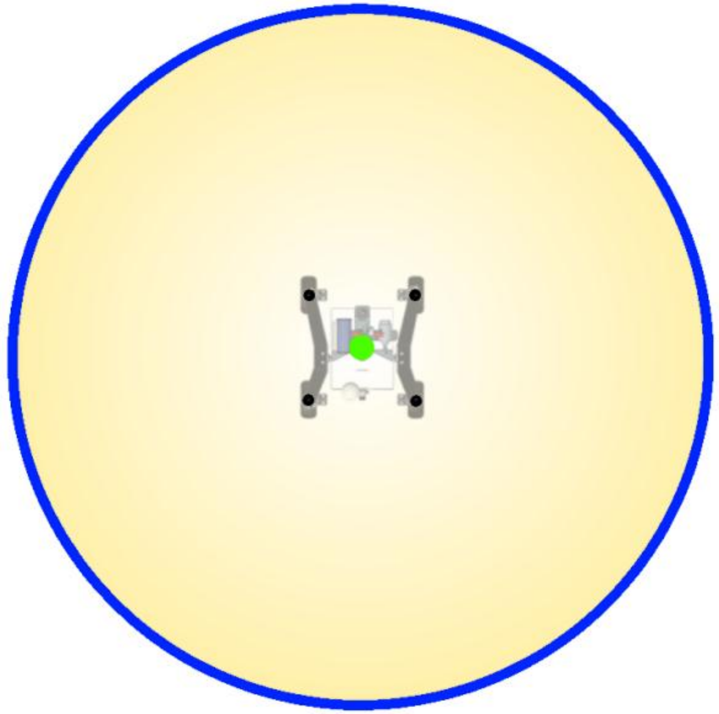
Future Work



Future Work
(The IC-Plane)

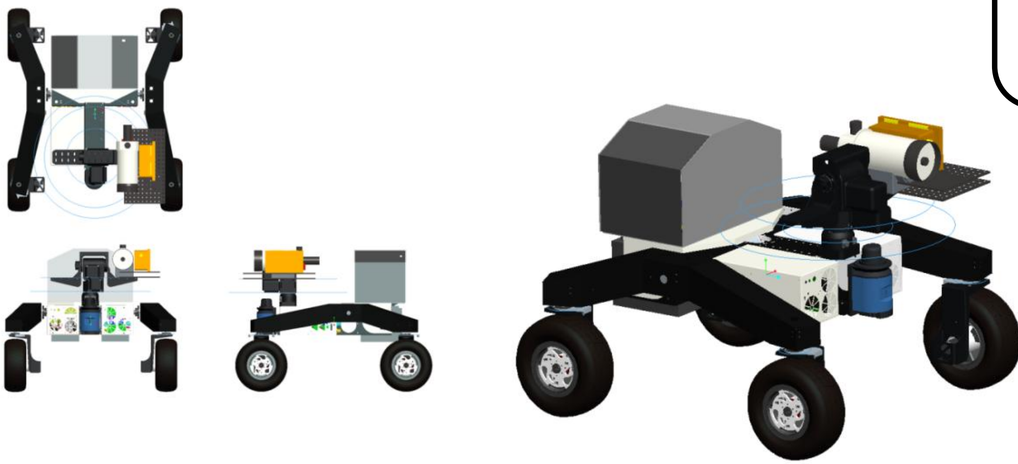
- True omnidirectionality: accessibility to the whole IC-Plane

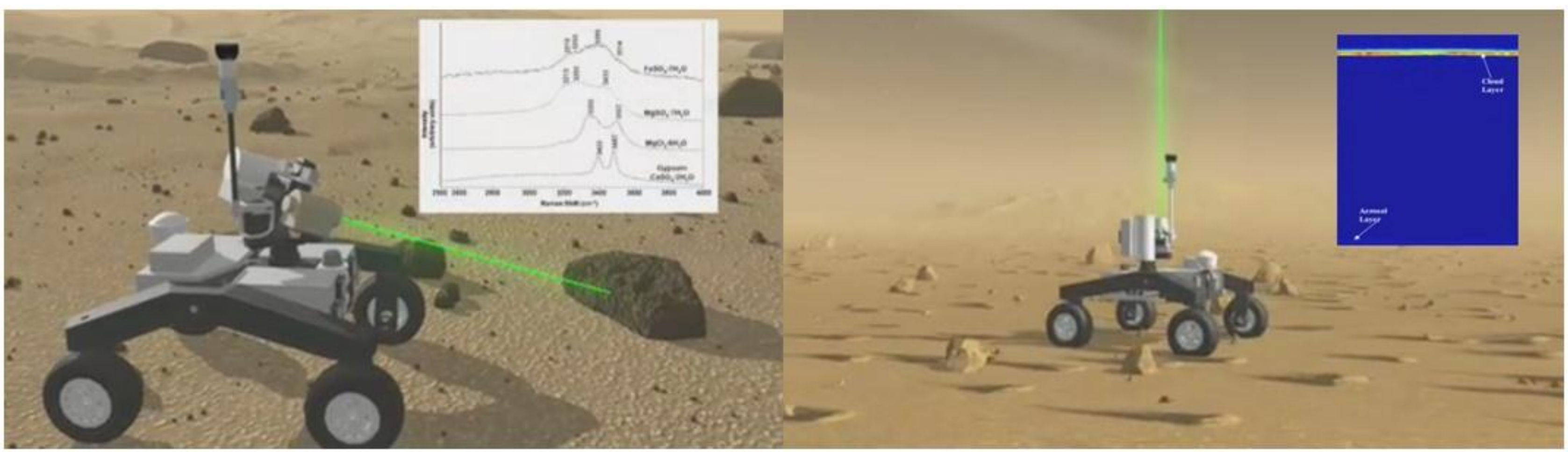




Future Work
(Laser based multi sensor)

- Targeting future Mars mission
- Under development to leave lab bench
- Topical and atmospheric measurements

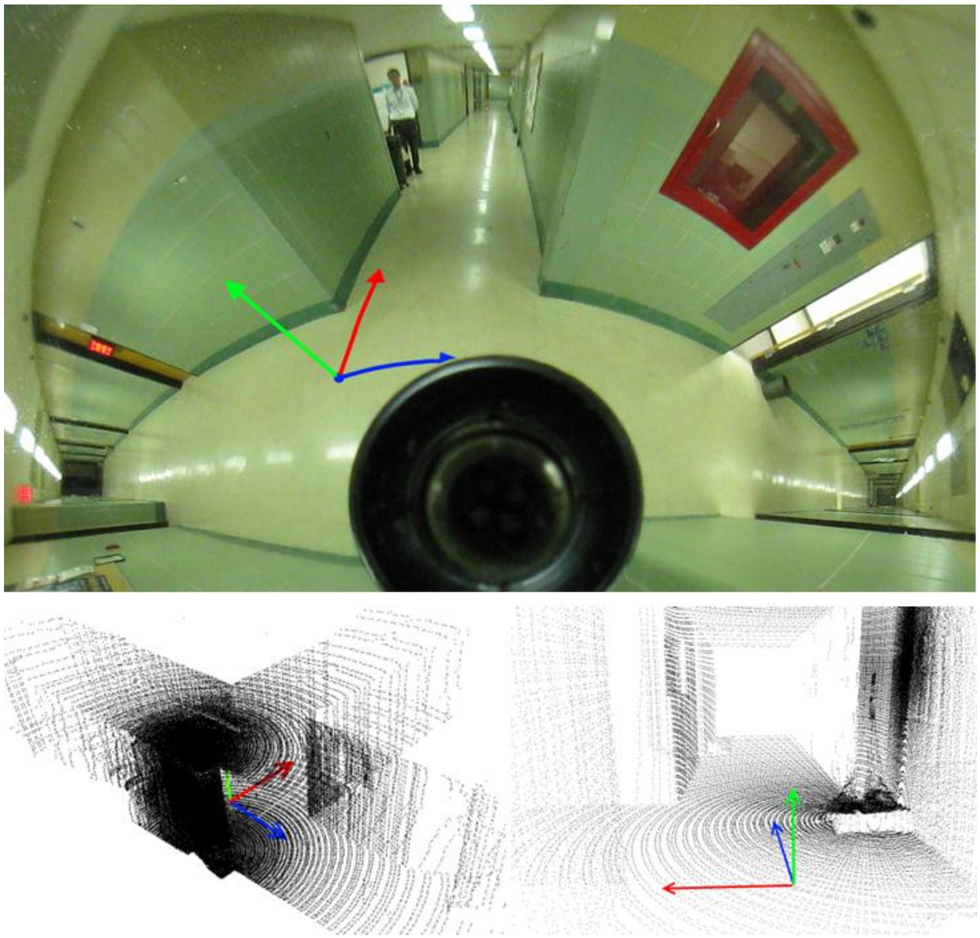


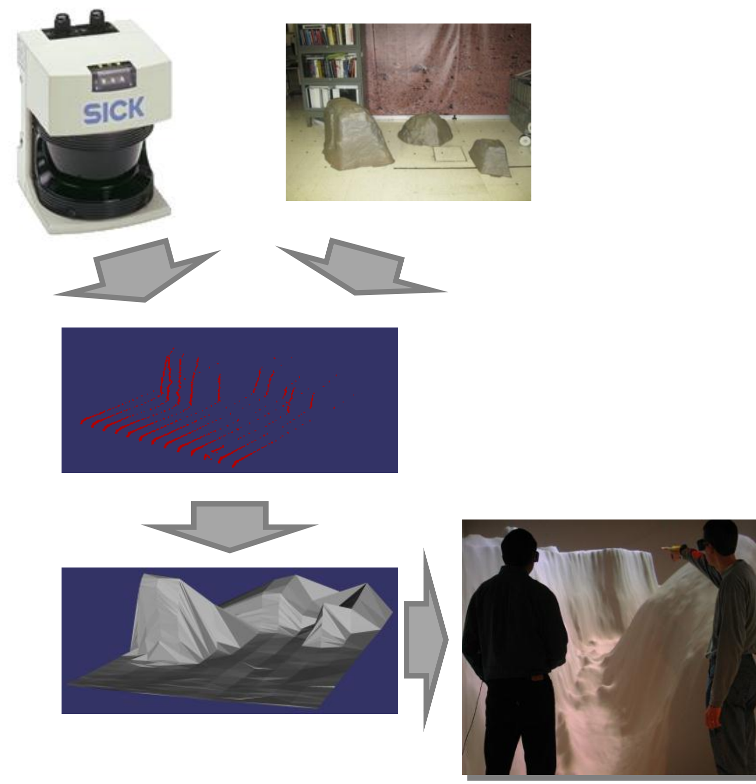


Future Work

(Immersive Virtual Human Environments)

- Make data from Moon, Mars, and other missions available to the public
- Data driven
- 3D media-rich interface
- Virtual reality

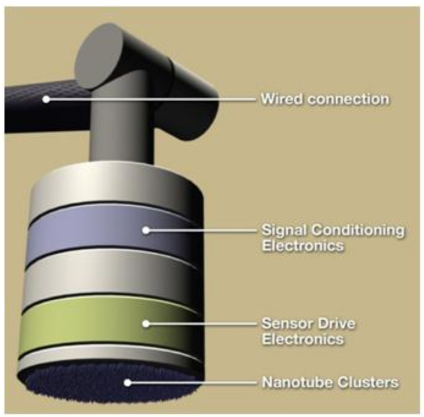


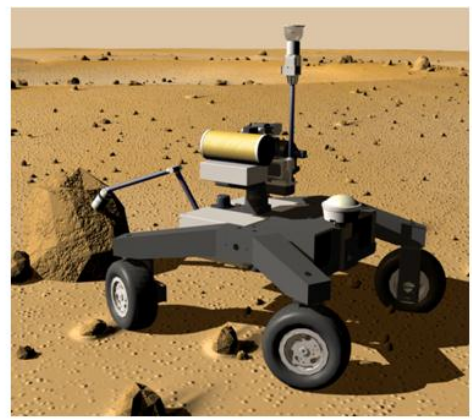


Future Work
(Bio exploration & X-Ray Fluoroscope)

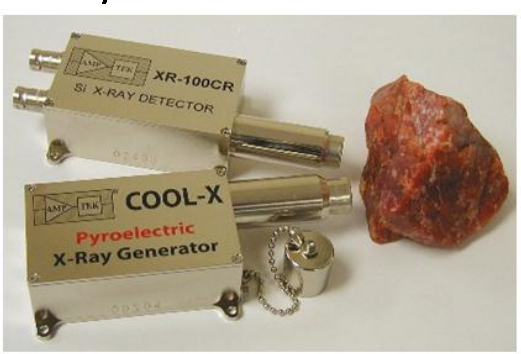
- Innovation work using a carbon nano-fiber-based bio-sensor to lead to autonomous exploration for life
- Borehole probe for sub-surface elemental analysis using x-ray fluorescence.

Carbon nano-fiber-based bio-sensor illustrations

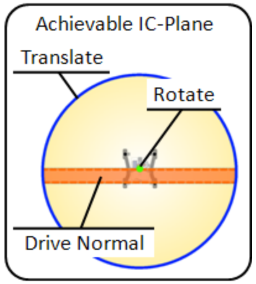




X-ray fluorescence borehole probe

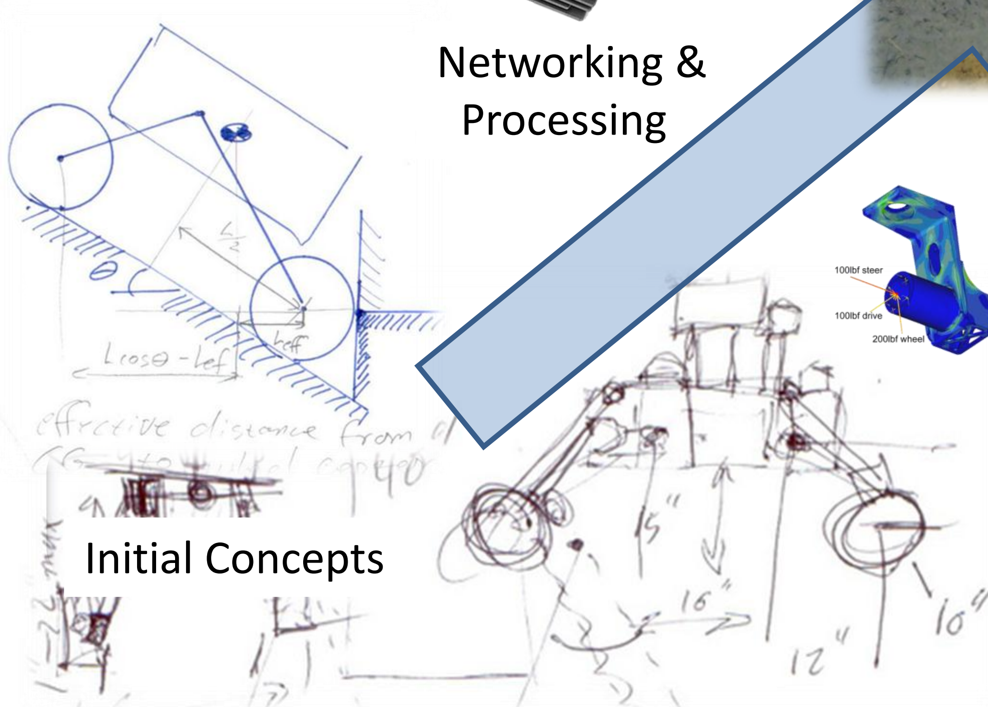


Conclusion

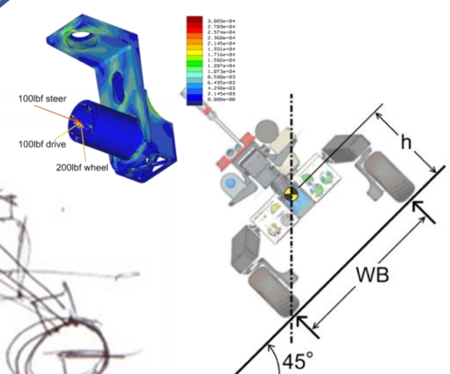


New Control Method

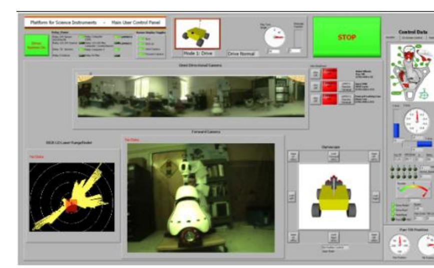
Networking & Processing

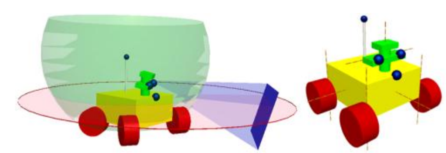


Initial Concepts



Mechanical Design & Analysis



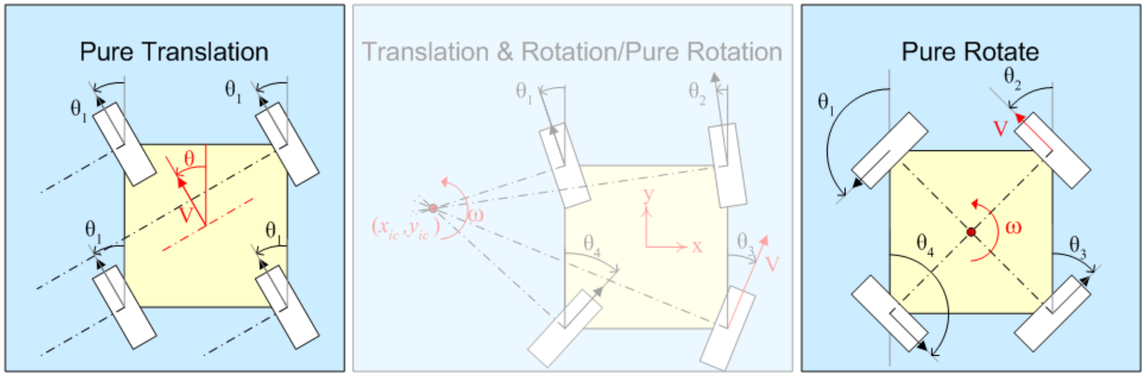


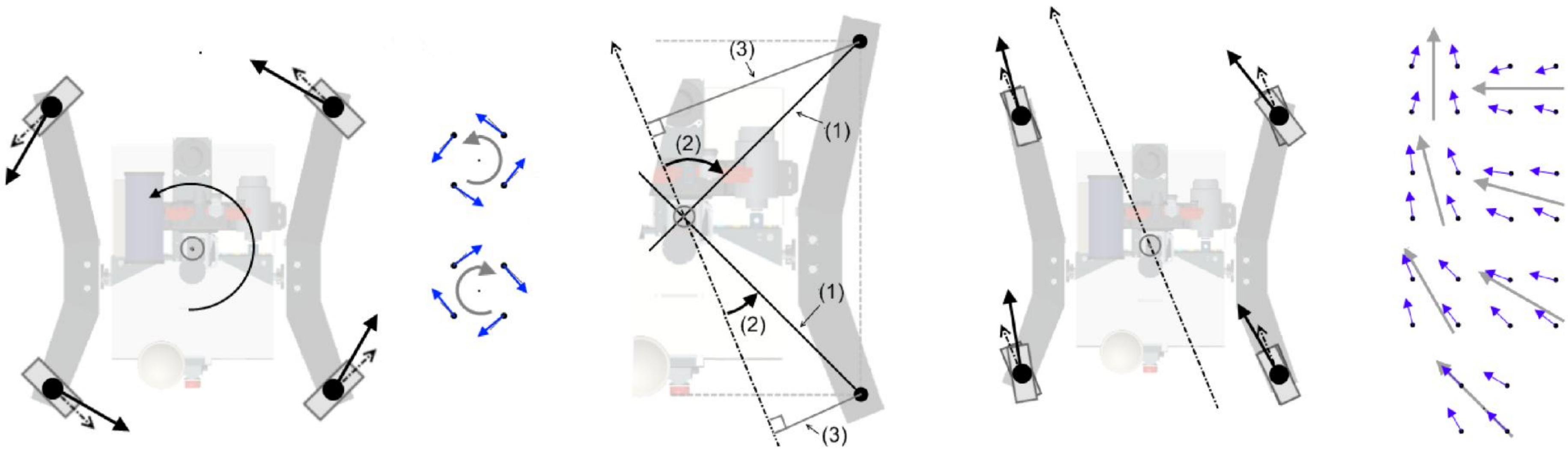
User Interface and Control

Backup

Translate & Rotate Modes

(Velocity and Trimming)





$$Trim_{wheel-i} = \sin(\angle DatumRef - \angle DirectionOfMotion)$$

Outline

& Rotate Modes