CLARAty: Towards Standardized Abstractions and Interfaces for Robotics Systems

Coupled Layer Architecture for Robotic Autonomy

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In Collaboration with
Ames Research Center
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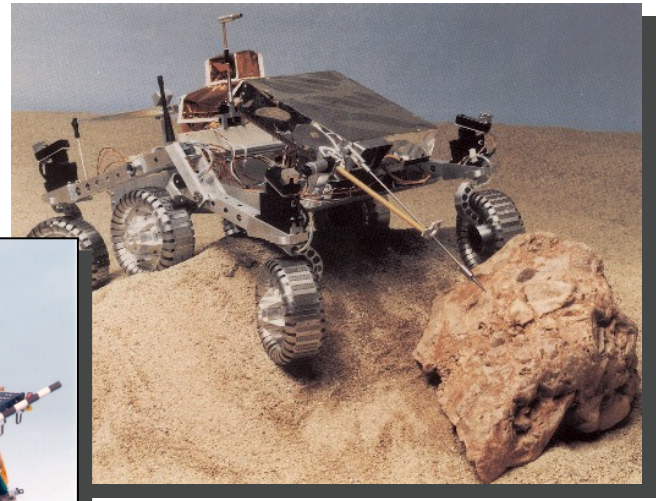
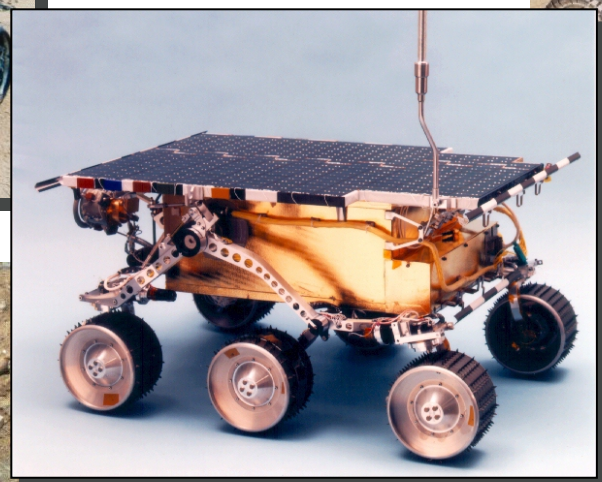
University of Minnesota

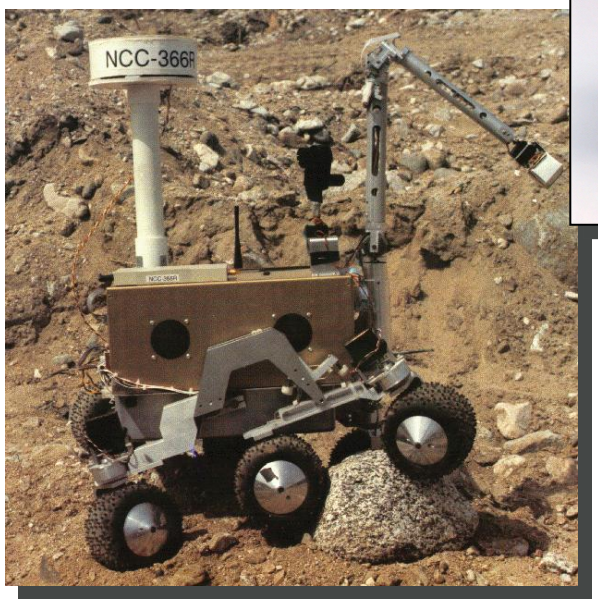
ICRA 2005 – Principle and Practice of Software Development in Robotics
April 18-22, 2005

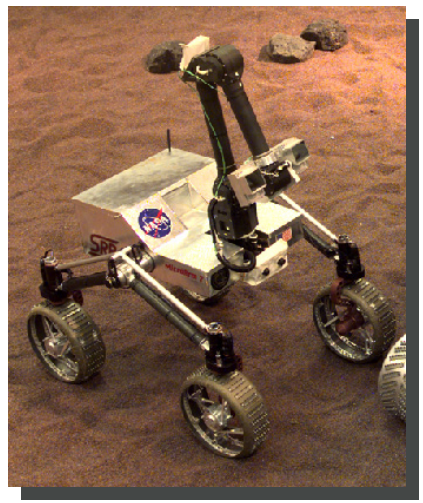
Motivation

Various Rovers Developed by JPL/NASA

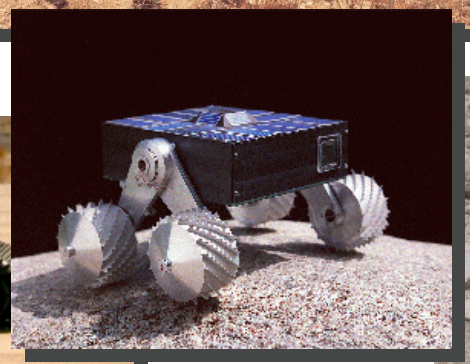








With Different Mobility Mechanisms

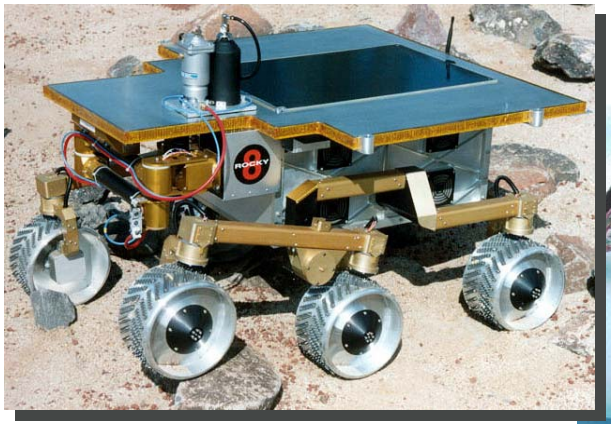


Problem and Approach

- Problem:
  - Difficult to share software across systems
  - Different hardware/software infrastructure
  - No standard protocols and APIs
  - No flexible code base of robotic capabilities

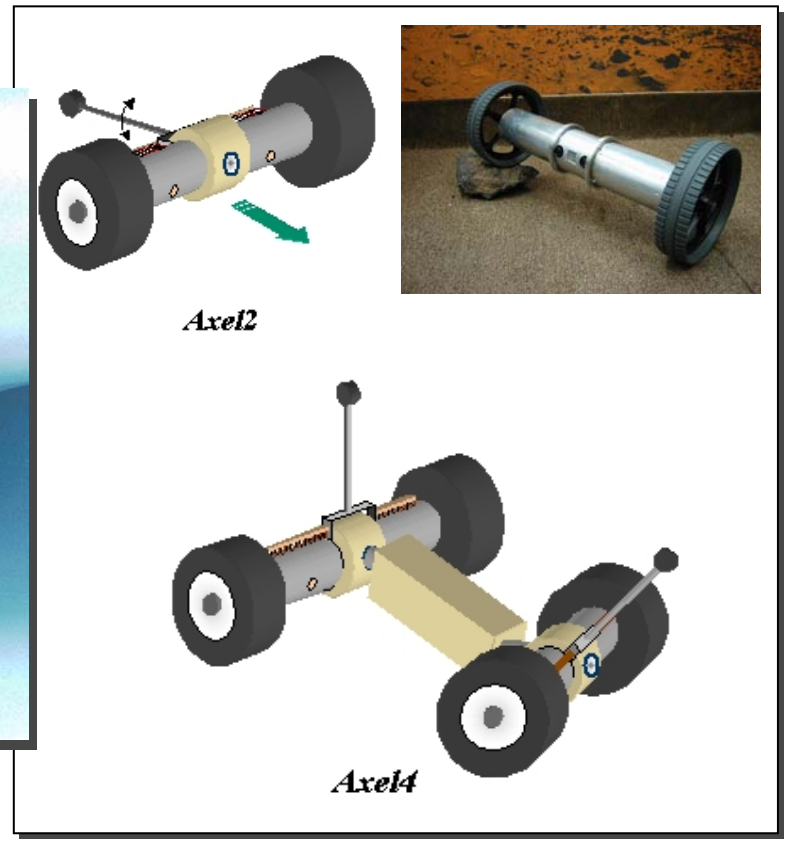
- Approach
  - Unified robotic framework
  - Capture and integrate legacy algorithms
  - Enable faster technology development
  - Operate heterogeneous robots

Would like to support …



Custom Rovers

Manipulators



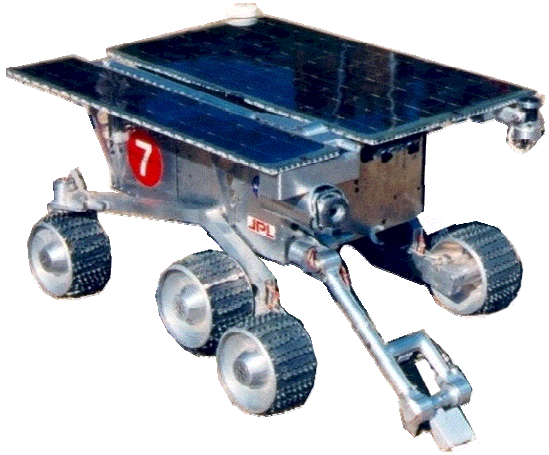
Reconfigurable Robots

COTS Systems

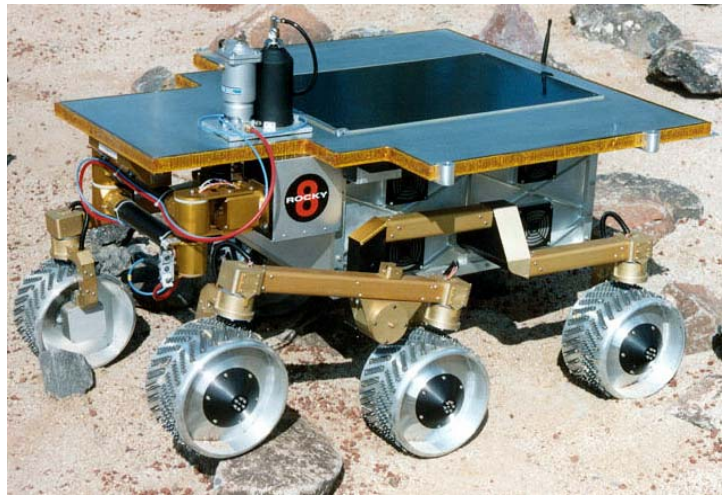
Challenges in Interoperability

- Mechanisms and Sensors
- Hardware Architecture
- Modular and Reusable Software Components

Locomotion



Rocky 7



Rocky 8

QuickTime™ and a None decompressor are needed to see this picture.

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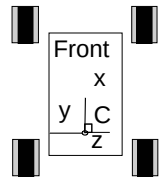
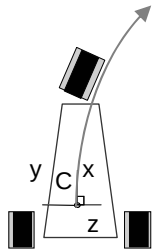
QuickTime™ and a None decompressor are needed to see this picture.

Reusable Wheeled Locomotion Algorithms

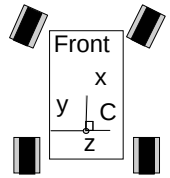
General flat terrain algorithms and specialized full DOF algorithms



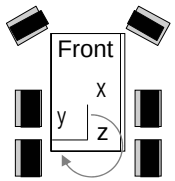
(a)
Skid Steering
(no steering wheels)



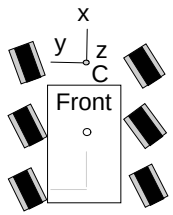
(b)
Tricycle
(one steering wheel)



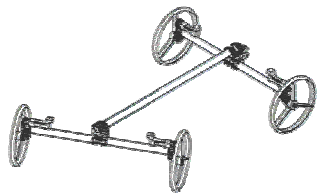
(c)
Two –wheel steering



(d)
Partially Steerable
(e.g. Sojourner,
Rocky 7)



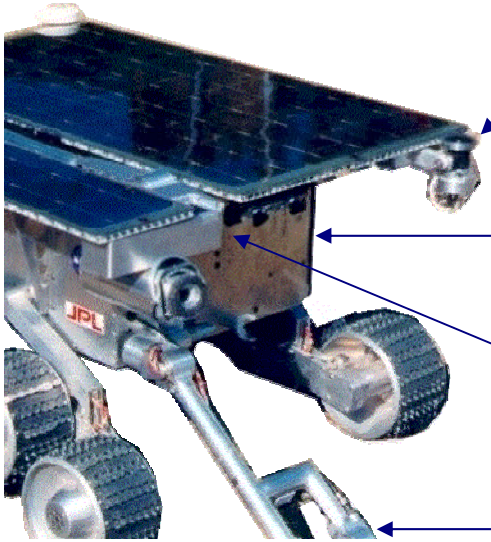
(e)
All wheel steering
(e.g. MER, Rocky8,
Fido, K9)



(f)
Steerable Axle
(e.g.Hyperion)

• • •

Manipulators and Sensor Suites



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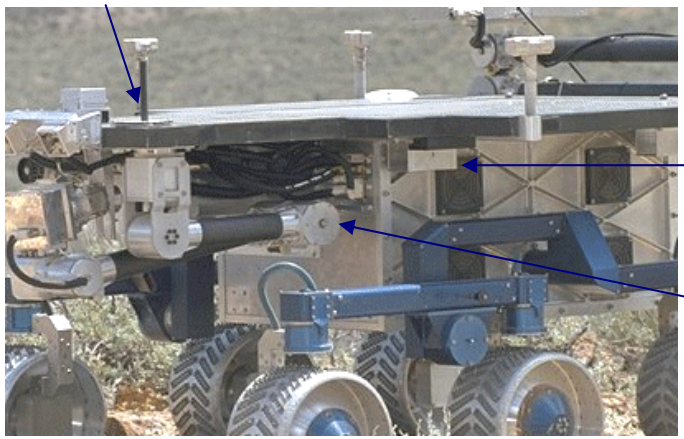
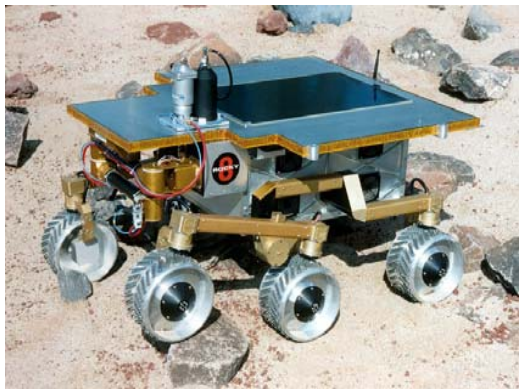


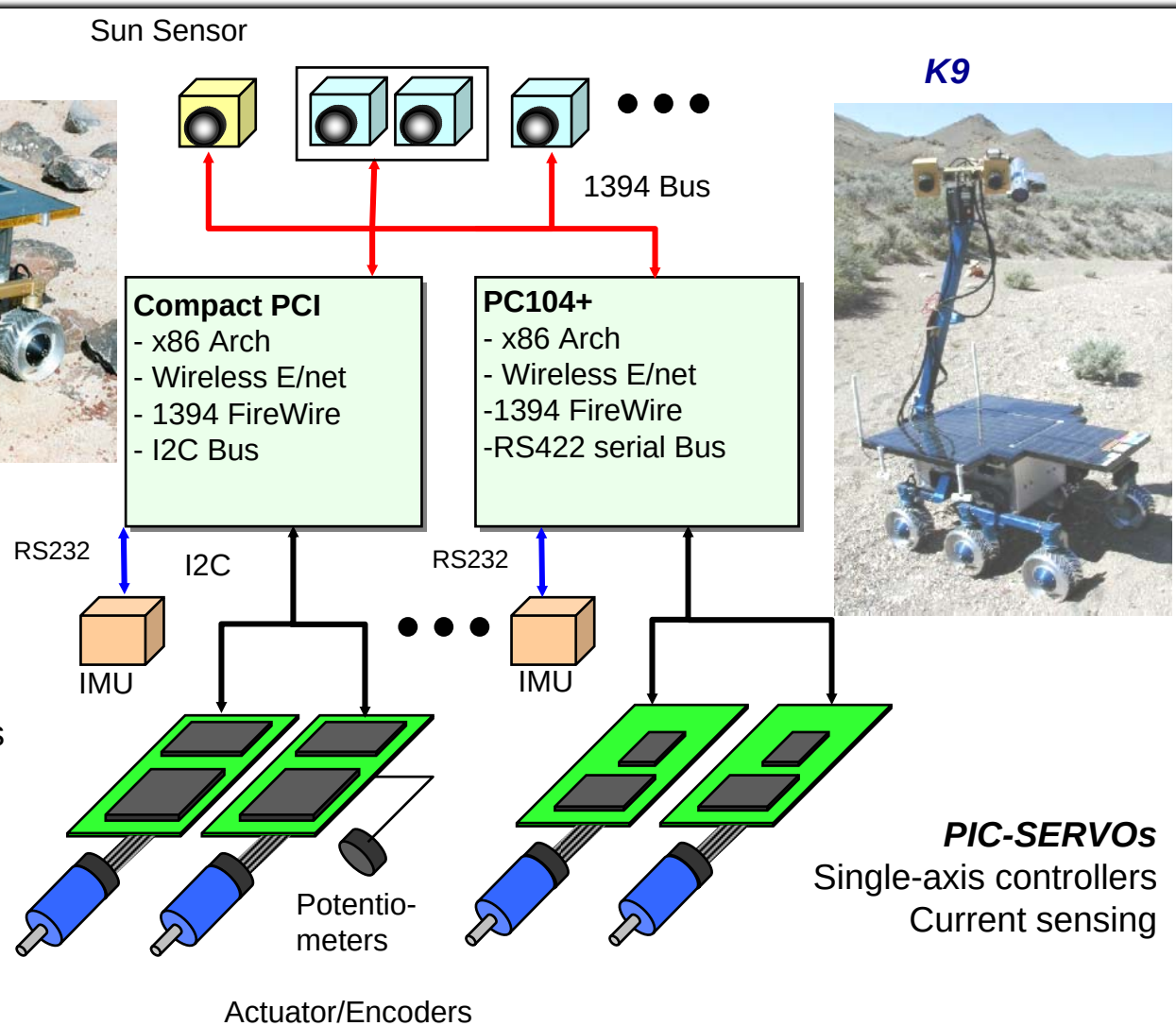
- Given different capabilities, how much reuse can be achieved?

Challenges in Interoperability

- Mechanisms and Sensors
- Hardware Architecture
- Modular and Reusable Software Components

Distributed Hardware Architecture



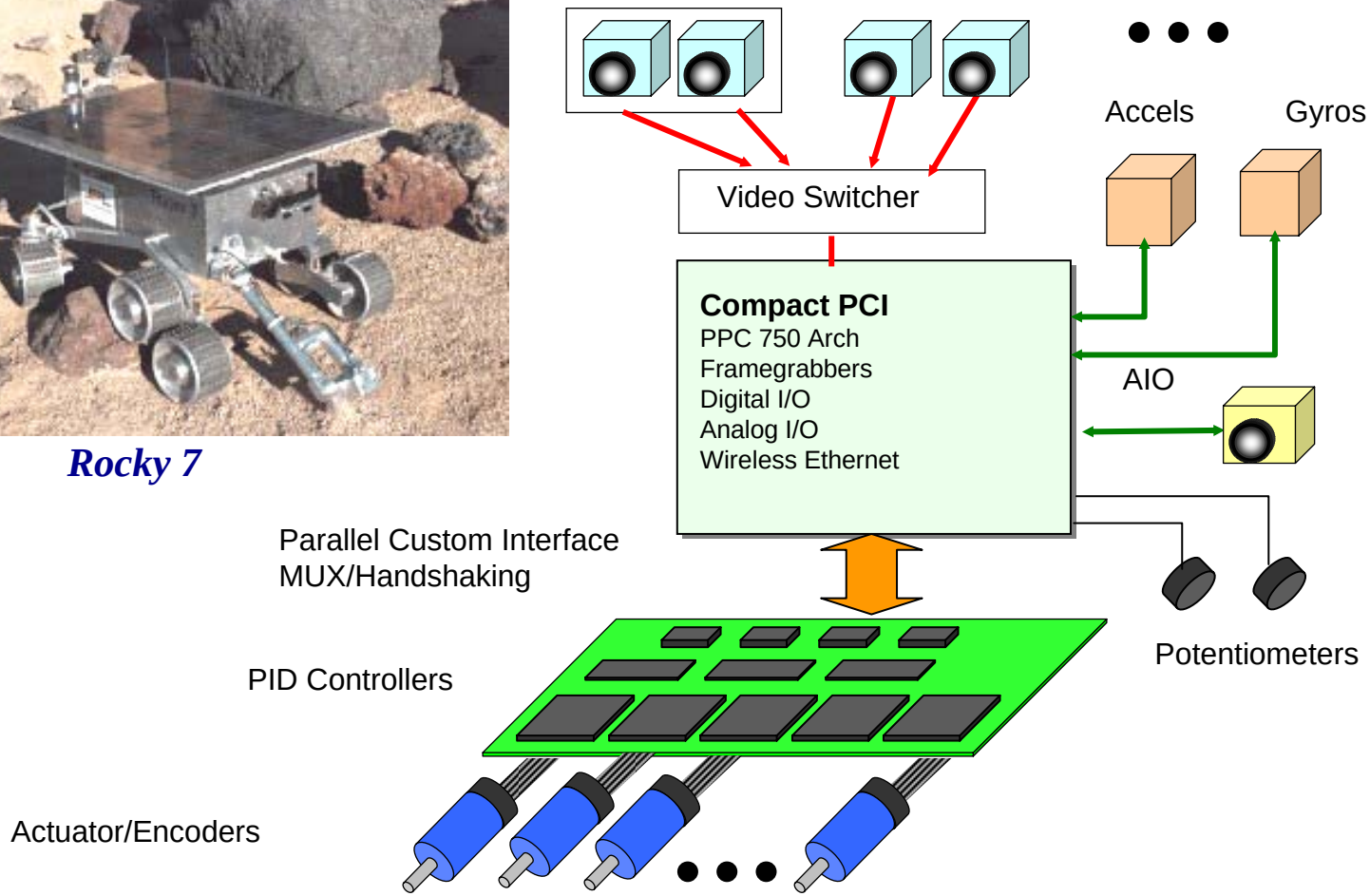


Rocky Widgets
Single-axis controllers
Current sensing
Digital I/O
Analog I/O

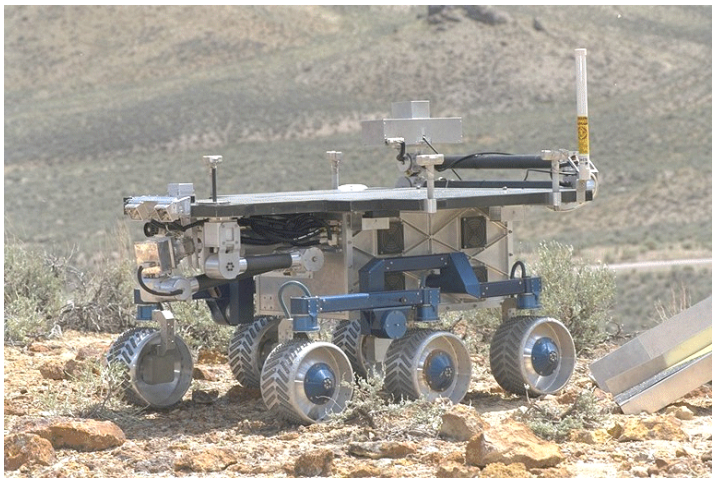
PIC-SERVOs
Single-axis controllers
Current sensing

Custom Architecture/Variability

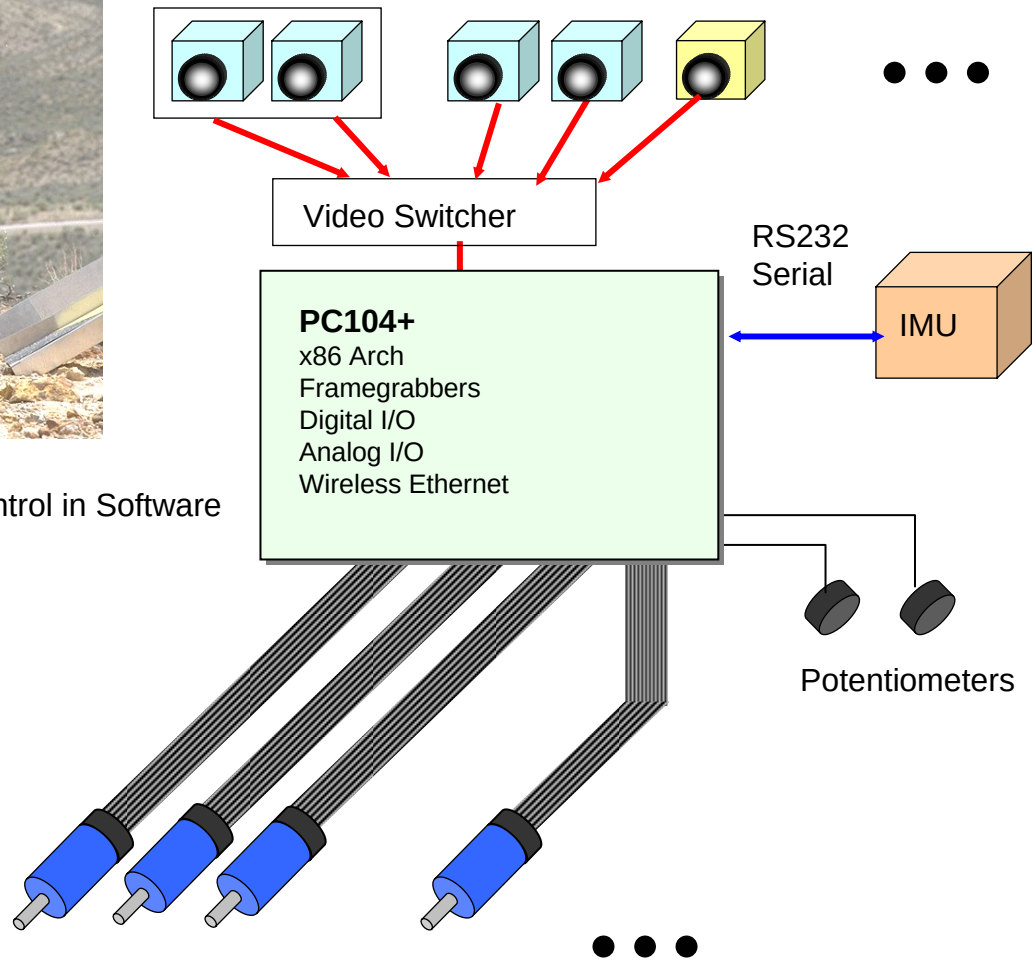
Rocky 7



Centralized Hardware Mapped Architecture



Fido



Challenges in Interoperability

- Mechanisms and Sensors
- Hardware Architecture
- Modular and Reusable Software Components

Designated Target Tracking for Single-Cycle Instrument Placement

QuickTime™ and a Video decompressor are needed to see this picture.

Integration of Complex Algorithms

- **I/O, motion control**
- **Trajectory Generation**
- **Rough Terrain Locomotion**
- **Odometry Pose Estimation**
- **Stereo Processing**
- **Visual Odometry**
- ***Obstacle avoidance***
- **Mast Control**
- **Visual Tracking**

Navigation with Path Planning on Two Rovers

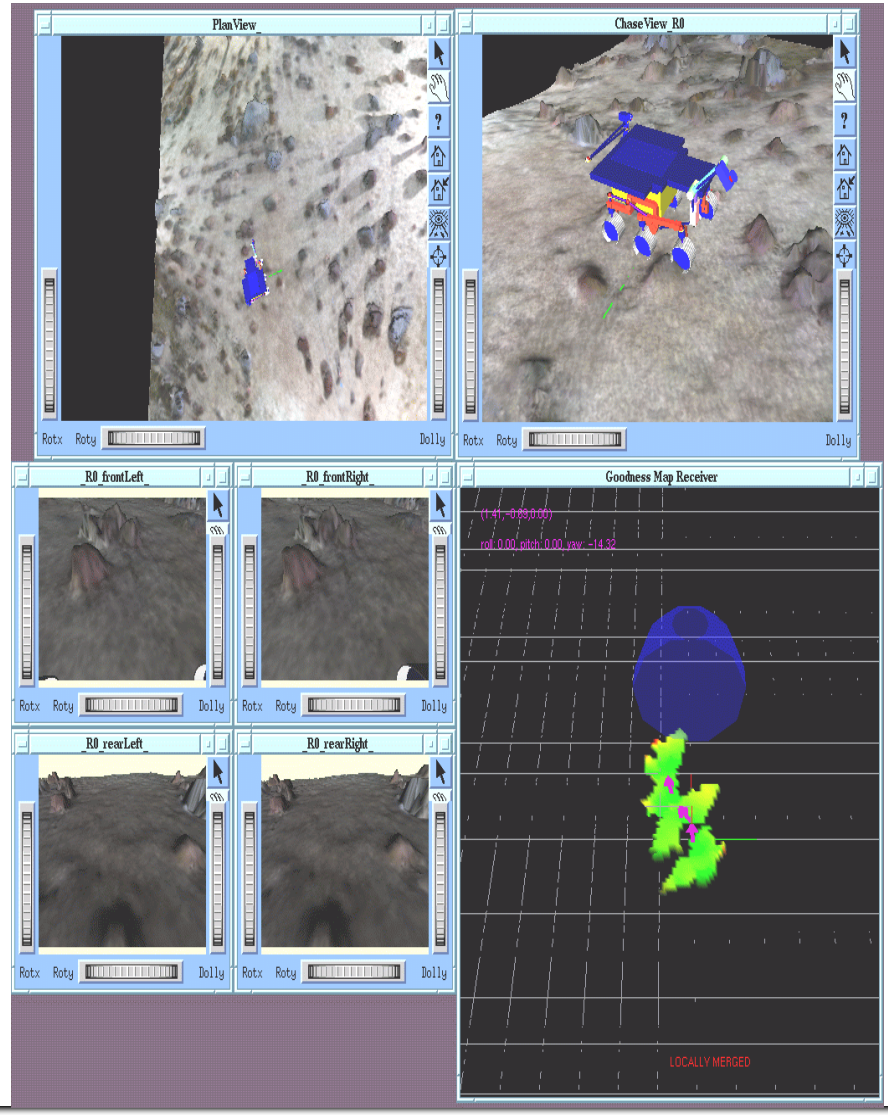
QuickTime™ and a Video decompressor are needed to see this picture.

Complex Algorithms on different Platforms

- I/O, motion control
- Trajectory Generation
- Rough Terrain Locomotion
- Odometry Pose Estimation
- Stereo Processing
- Visual Odometry
- Navigation (Morphin)
  - Obstacle avoidance
  - Path Planning

And with a Simulated Rover

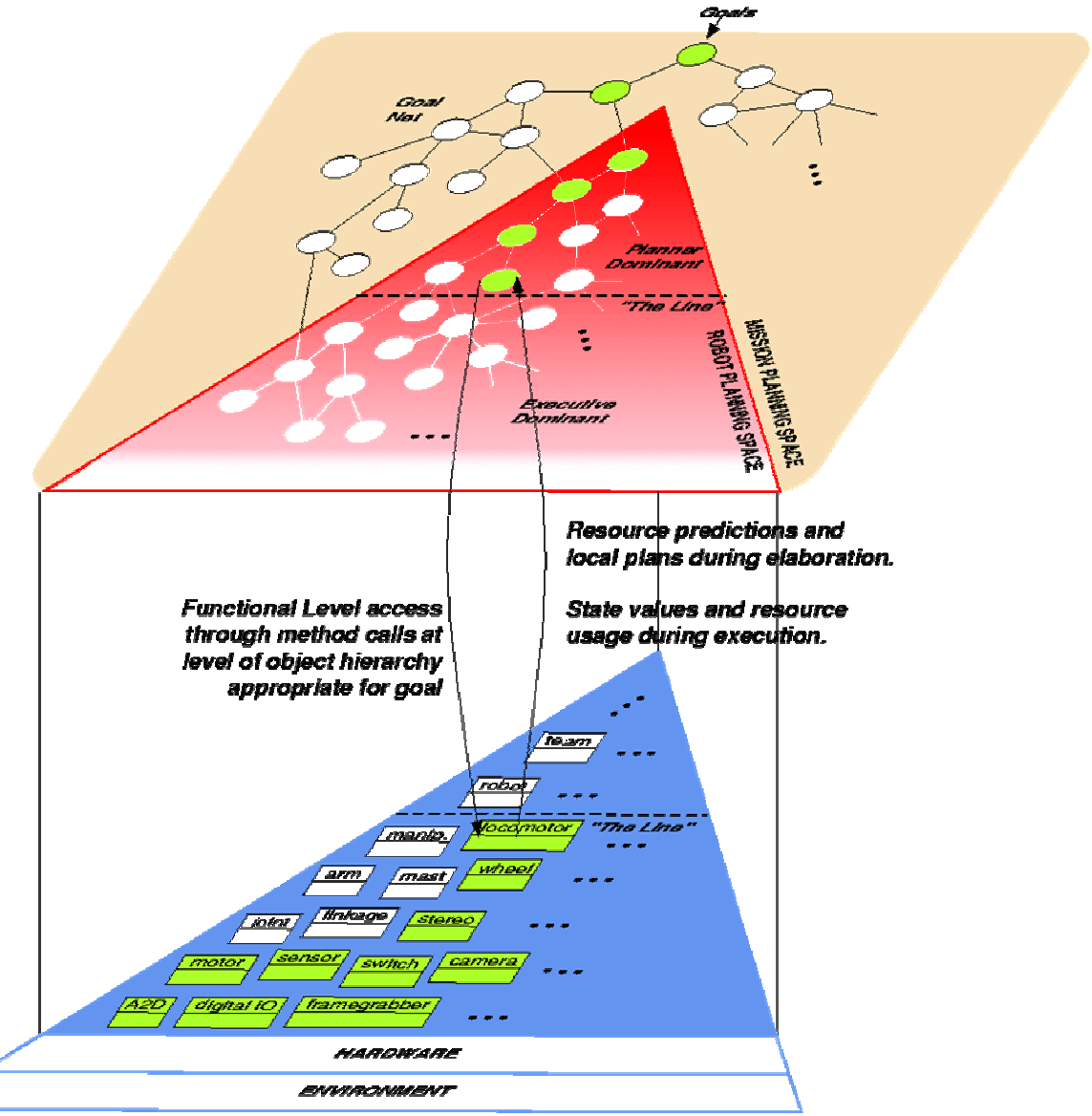
QuickTime™ and a Video decompressor are needed to see this picture.



Technical Approach

A Two-Layered Architecture

CLARAty = Coupled Layer Architecture for Robotic Autonomy



THE DECISION LAYER:

Declarative model-based
Global planning

INTERFACE:

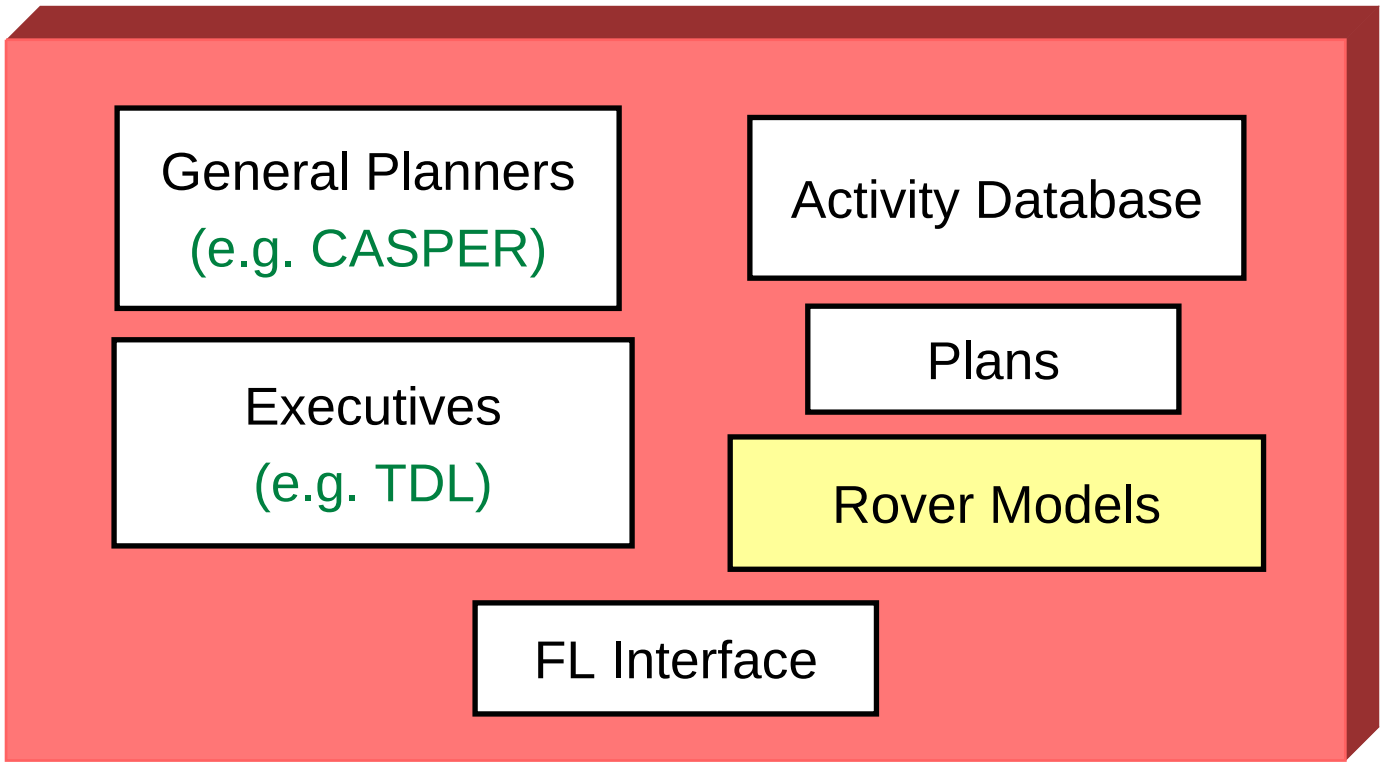
Access to various levels
Commanding and updates

THE FUNCTIONAL LAYER:

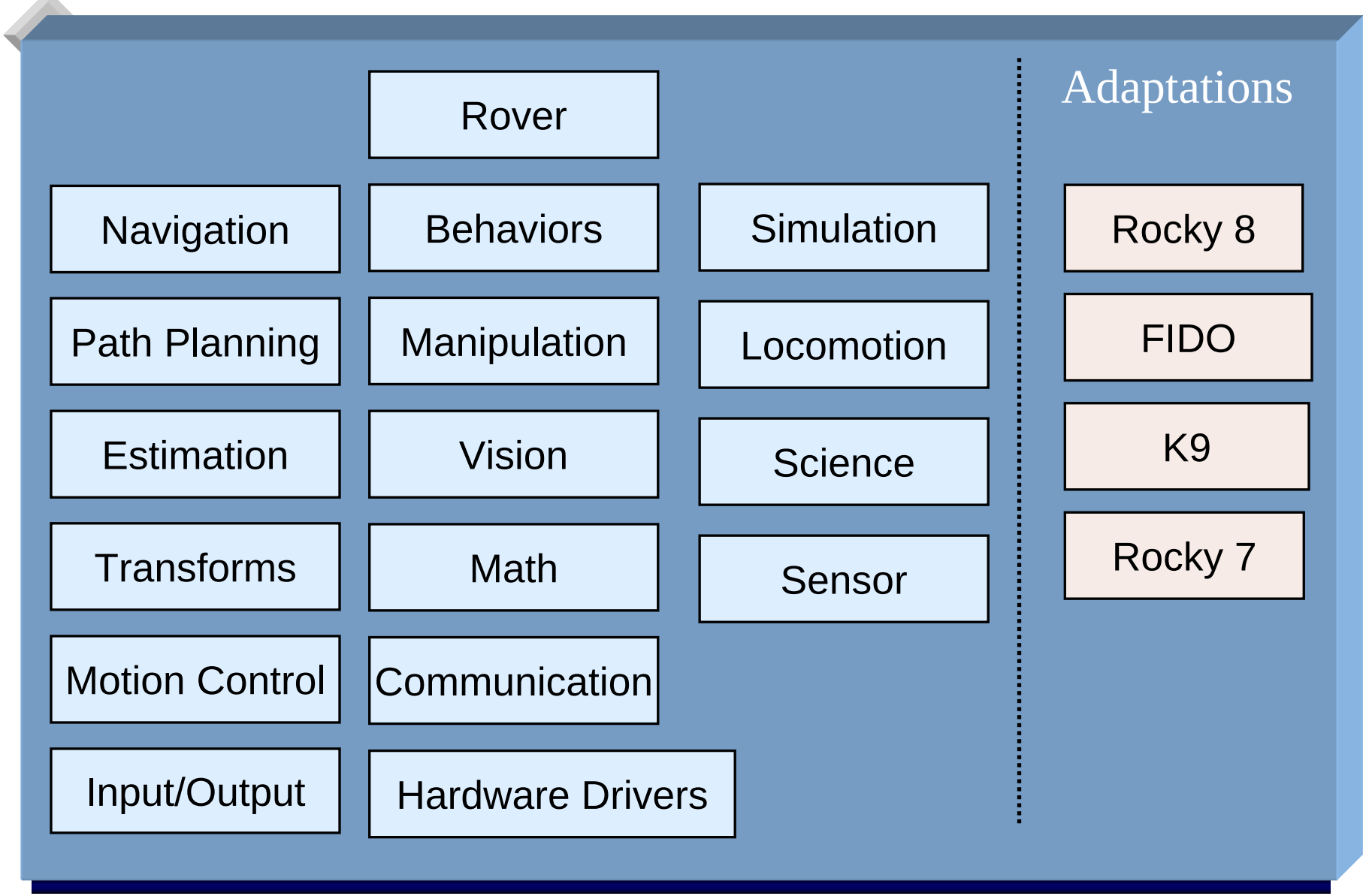
Object-oriented abstractions
Autonomous behavior
Basic system functionality

Adaptation to a system

The Decision Layer

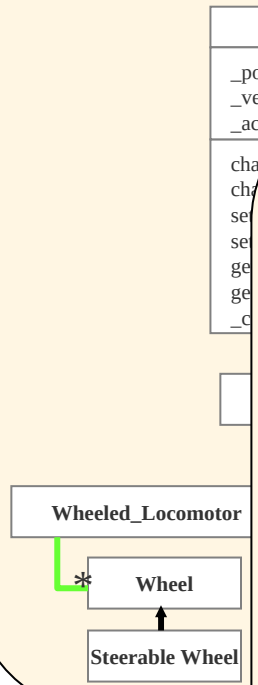


The Functional Layer

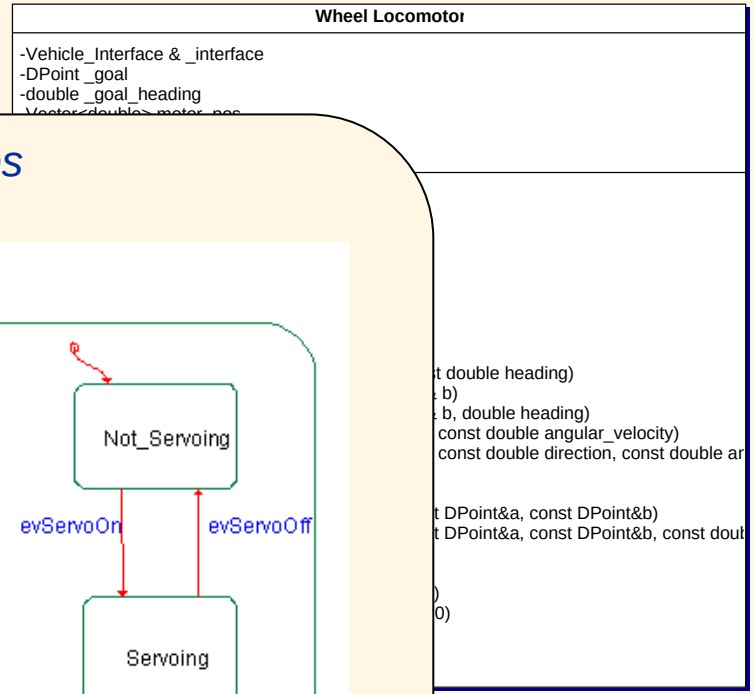


Standardizing Base Abstractions

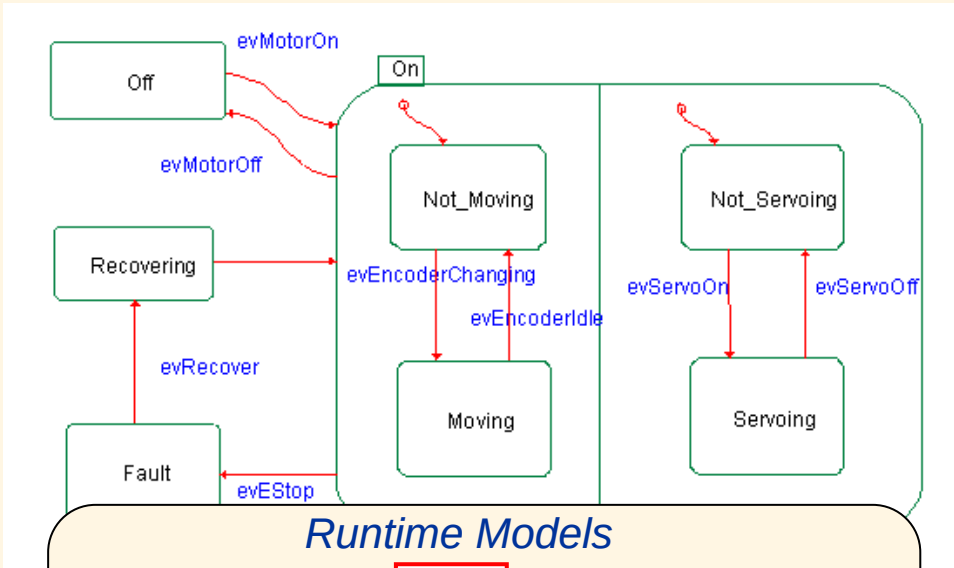
Abstractions



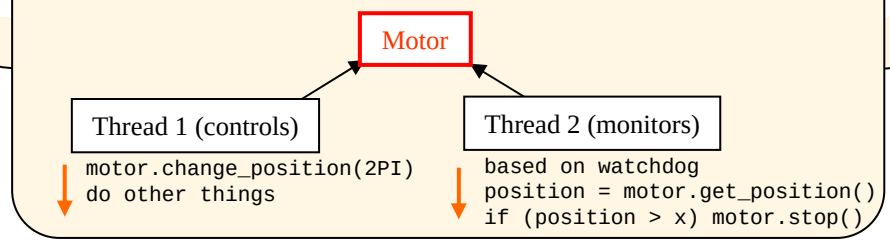
APIs and Behaviors



State Machines

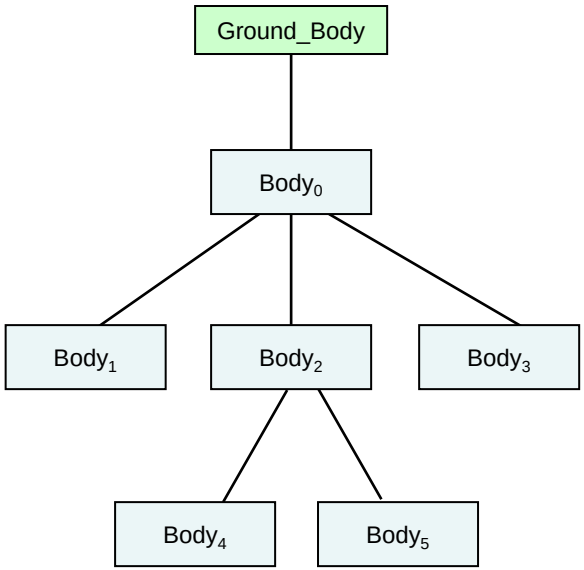


Runtime Models



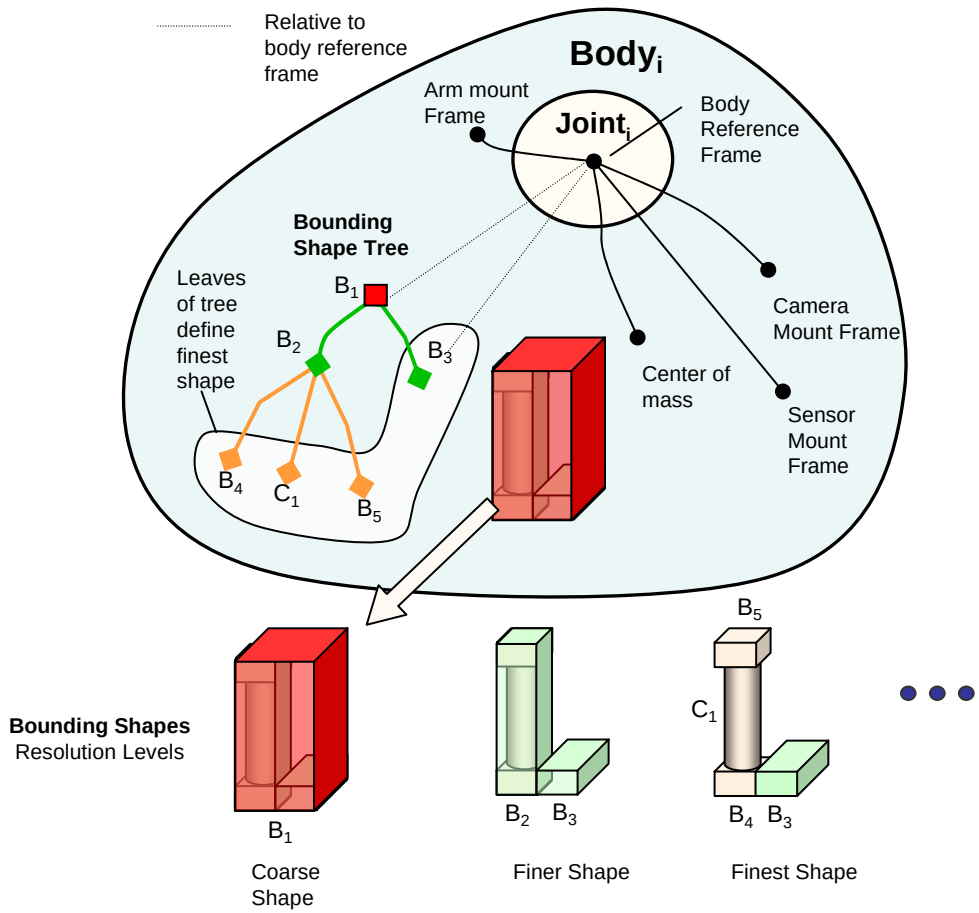
Unified Mechanism Model

Body Tree

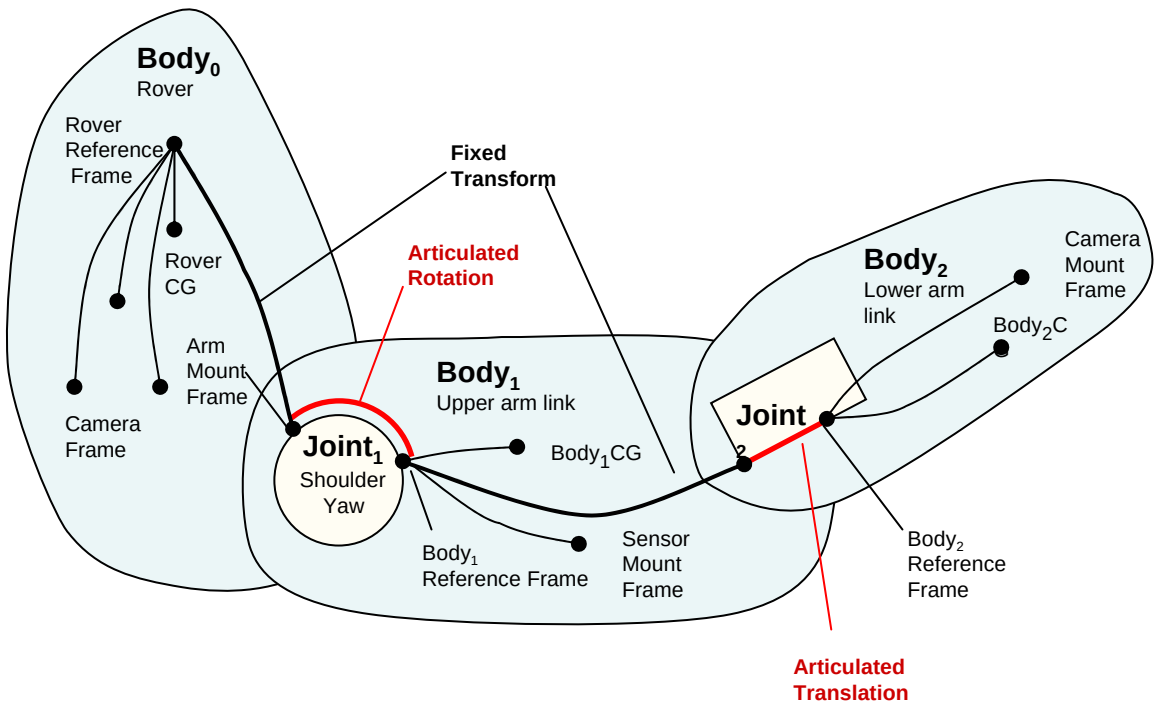


Mechanism Tree

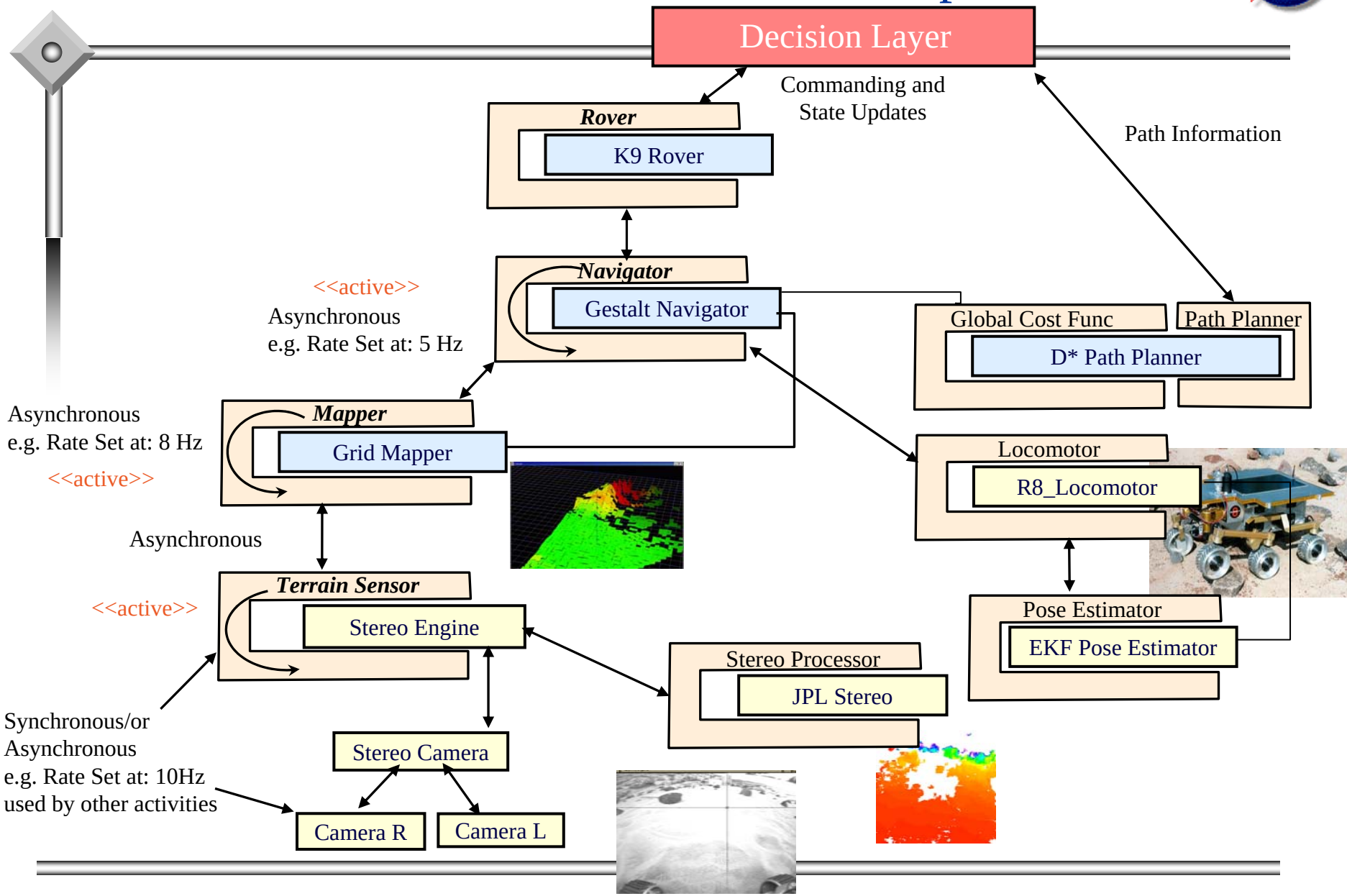
Bodies and Joints



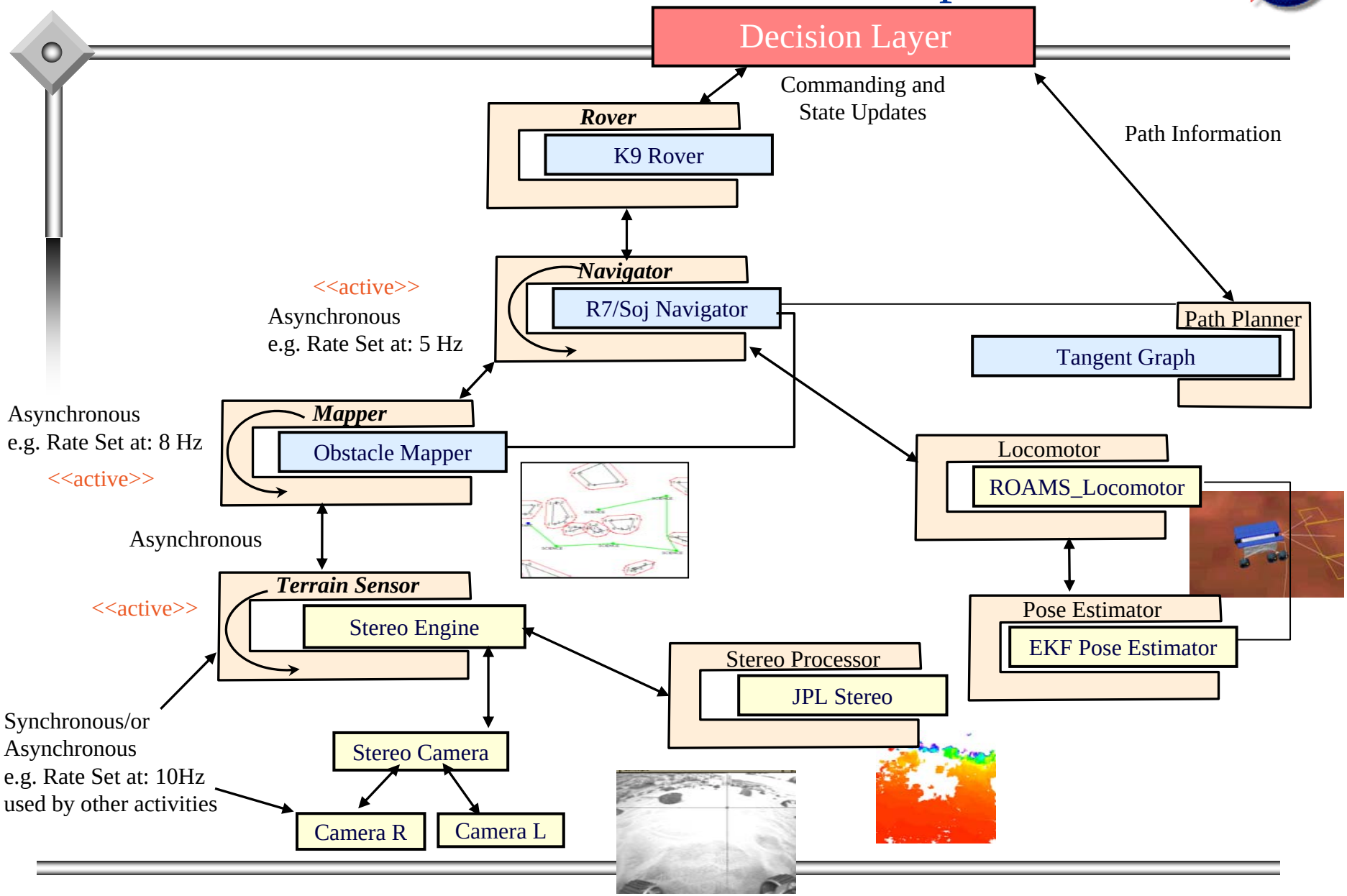
Connecting Bodies and Joints



Architectural Traverse Example



Architectural Traverse Example



Some Results on Reusability

Some Software Inter-operability Statistics

Algorithm Description	1st Adaptation		Subsequent Adaptations (time in days)		
	On	Time	On	Adapt.Time	Tuning Time
3D Extended Kalman Filter for Rover Pose Estimation	Rocky 8	60	FIDO (JPL)	1	3
3D Locomotion for wheeled vehicles	Rocky 7	30	Rocky 8 (JPL)	10	12
			FIDO (JPL)	1	1
			K9 (ARC)	4	1
Morphin Navigator	Rocky 8	75	FIDO (JPL)	1	1
			K9 (ARC)	4	14
			ROAMS (JPL)	1	-
Mast Control Software	Dexter	21	Rocky 8 (JPL)	7	7
			FIDO (JPL)	4	1

Code Reusability for Motion Control

Rocky 7 Modules	Lines of Code	Status
Controlled Motor	2,652	Reusable
Input Output	2,690	Reusable
Bits	1,580	Reusable
Resources (Timers, etc)	725	Reusable
Rocky 7 Motor	927	Non-reusable
Rocky 7 H/W Maps	841	Non-reusable
Motor Controlller LM629	1,143	R
Digital I/O Board (S720)	576	R
PCI Components	329	R
Total	11,463	
Total Reusable	**85%**	
Total Reusable - Strict	**67%**	

Rocky 8 Modules	Lines of Code	S
Controlled Motor	2,652	R
Trajectory Generator	691	R
Input Output	2,690	R
Bits	1,580	R
Resources (Timers, etc.)	725	R
Bits	756	Reusable
Rocky 8 Motor	1,180	Non-reusable
Rocky 8 H/W Maps	626	Non-reusable
Widget Board Software	2,126	Reusable - widget
Motor Controller HCTL	900	Reusable - HCTL
I2C Master	1,165	Reusable - I2C
I2C Master Tracii	1,223	Reusable - Tracii
Total	16,314	
Total Reusable	**89%**	
Total Reusable - Strict	**56%**	

FIDO Modules	Lines of Code	Status
Controlled Motor	2,652	Reusable
Trajectory Generator	691	Reusable
PID Controller	997	Reusable
Input Output	2,690	Reusable
Bits	1,580	Reusable
Resources (Timers, etc)	725	Reusable
Common Definitions	2,380	Reusable
FIDO Motor	2,086	Non-reusable
FIDO H/W Maps	1,494	Non-reusable
Encoder Counter (ISA P 400)	463	Reusable - H/W
Analog Input Board (MSI P415)	519	Reusable - H/W
Analog Output Board (MSI P460)	462	Reusable - H/W
Digital I/O Board (MSI P560)	602	Reusable - HCTL
Total	17,341	
Total Reusable	**79%**	
Total Reusable - Strict	**68%**	

Code Resuability for Locomotion Example

Module	Lines of Code	Status	Depends On
Wheel Locomotor	1445	Reusable	Motion Sequence, 1D Solver, Homogeneous Transforms
Motion Sequence	540	Reusable	Vector
Matrix, Vector, Array	1083	Reusable	-
1D Solver	356	Reusable	-
Location, Homogeneous Transforms	341	Reusable	Rotation Matrix, Point 2D
Rotation Matrices	435	Reusable	-
Point 2D	131	Reusable	-
Controlled Motor	2080	Reusable	
Rocky 8 Locomotor	250	Non-reusable	Rocky 8 Motor
Rocky 8 Motor	334	Non-reusable	Widget Motor, etc...
Total	6995	584 (non-reusable)	
Total Reusable	**~92%**		

Conclusions

- Use abstraction to master complexity
- Encapsulate and abstract hardware variations
- Provide multi-level access through Decision Layer for fault diagnosis and recovery
- Use domain expertise to guide design
- Make all assumptions explicit
- Stabilize external interfaces rapidly
- Document processes and products well
- Avoid over-generalization - define scope
- Encapsulate system specific runtime models
- Do not comprise performance - least common denominator solutions are unacceptable in hw/sw interactions
- Standardize Hardware

Acknowledgements

CLARAty Team (multi-center)

Jet Propulsion Laboratory

- ROAMS/Darts Team
- CLEaR Team
- Instrument Simulation Team
- Machine Vision Team
- FIDO Team

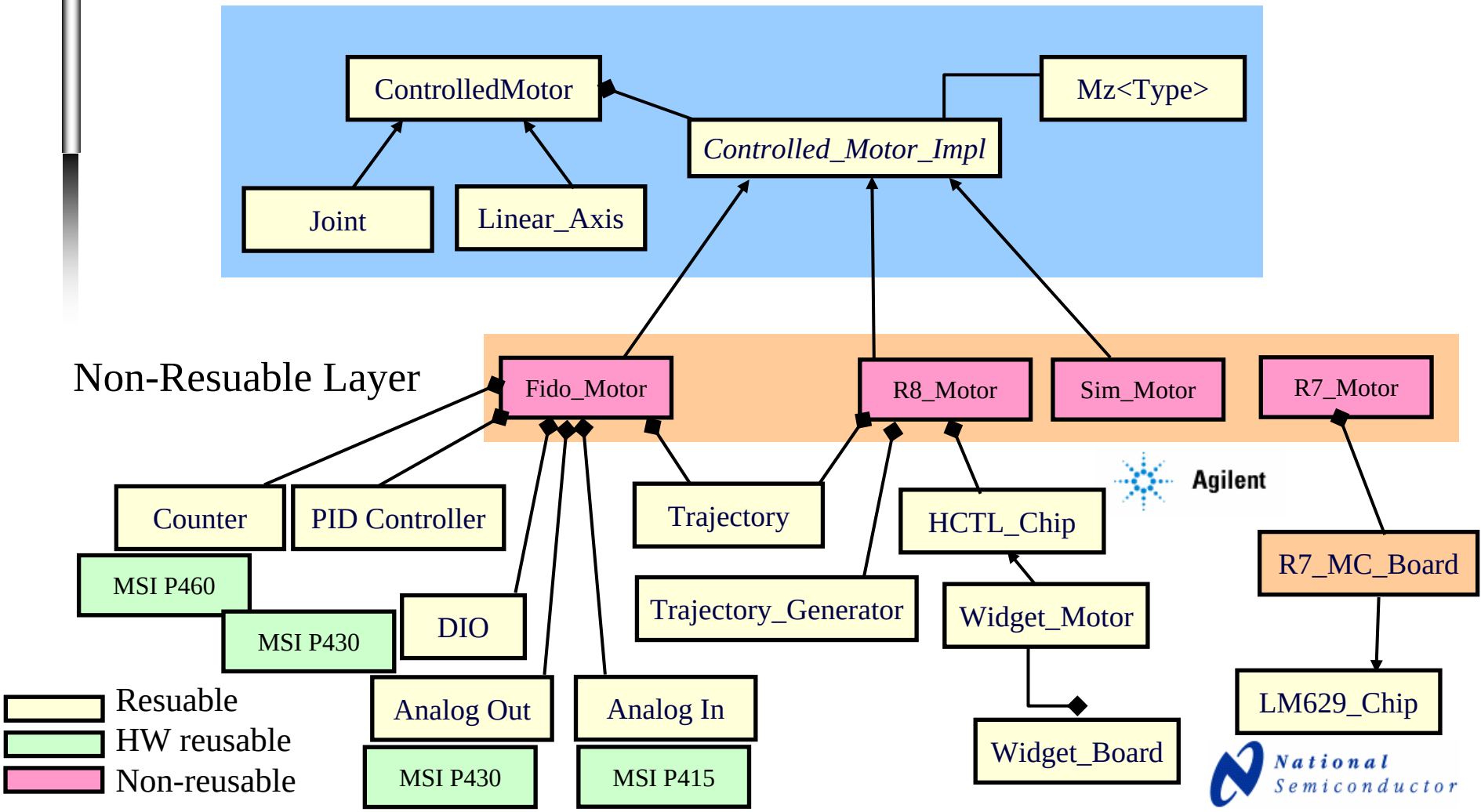
Ames Research Center

- K9 Team

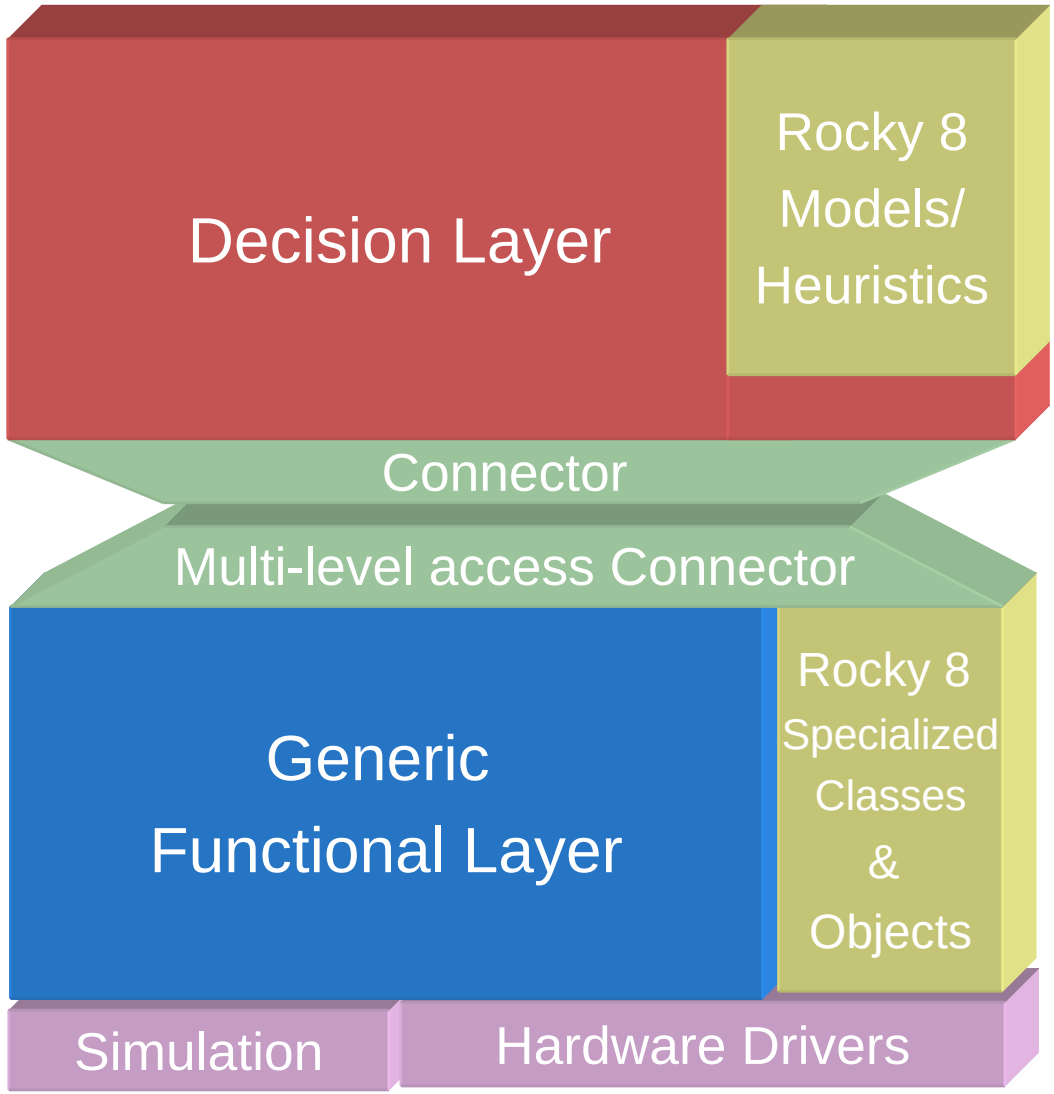
Carnegie Mellon University

Thank you for your Attention

Examples of CLARAty Reusability



Adapting to a Rover



Supported Platforms

Rocky 8

VxWorks x86

JPL

K9

Linux

x86

Ames

Rocky 7

VxWorks ppc

JPL

FIDO

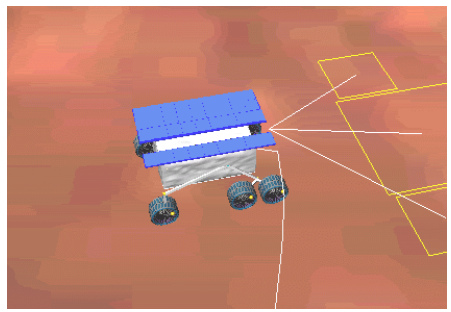
VxWorks x86

JPL

ATRV

Linux x86

CMU



ROAMS

Solaris Linux

JPL

CLARAty Team

- **NASA Ames Research Center**
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  - Anne Wright *(Cog-E & Core lead)*

- **Carnegie Mellon University**
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  - Chris Urmson
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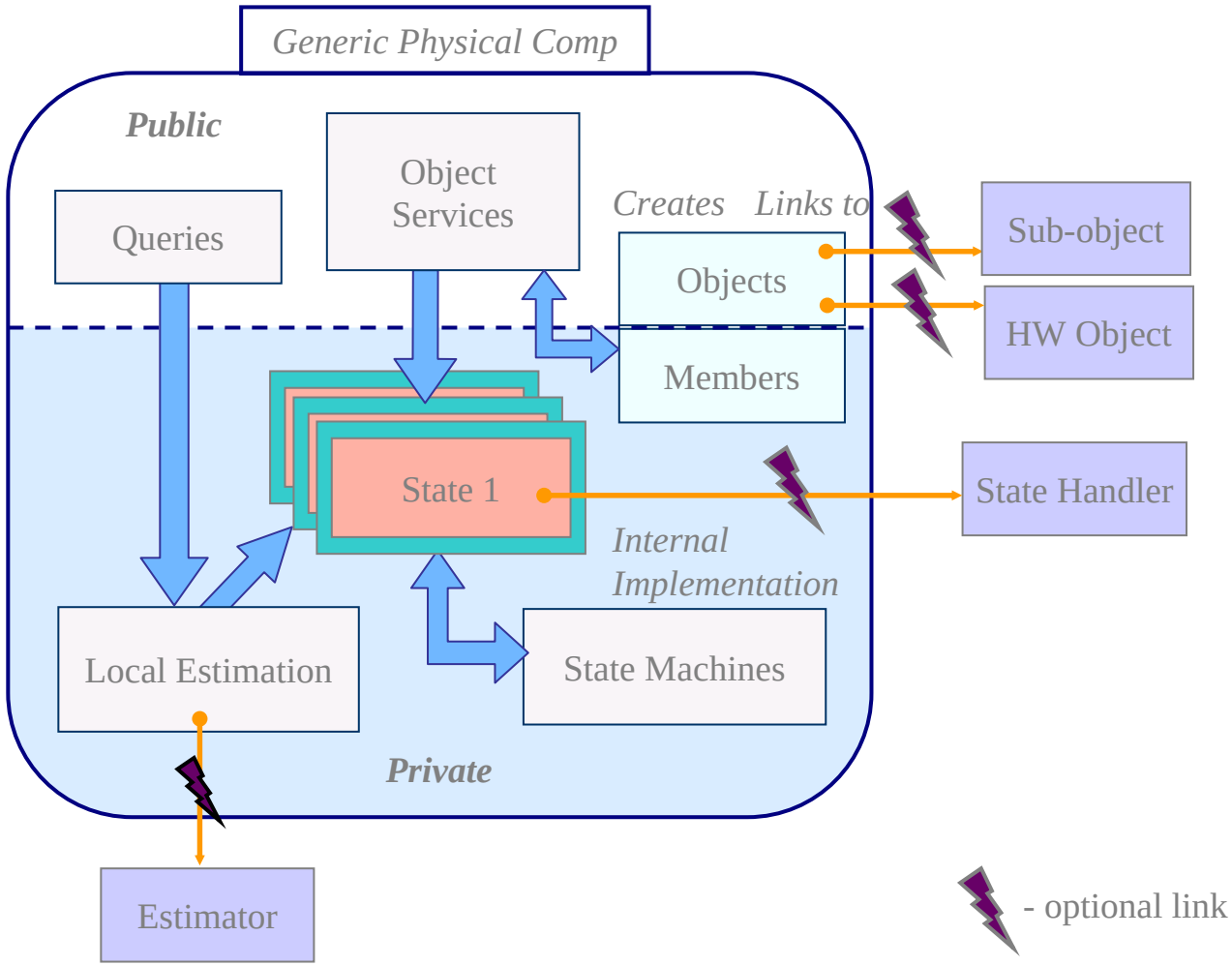
  - Won Soo Kim (34) *(Motion lead)*
  - Michael Mossey (31)
  - Issa A.D. Nesnas (34) *(Task Manager)*
  - Richard Petras (34) *(Adaptation lead)*
  - Marsette Vona (34)
  - Barry Werger (34)

- **OphirTech**
  - Hari Das Nayar

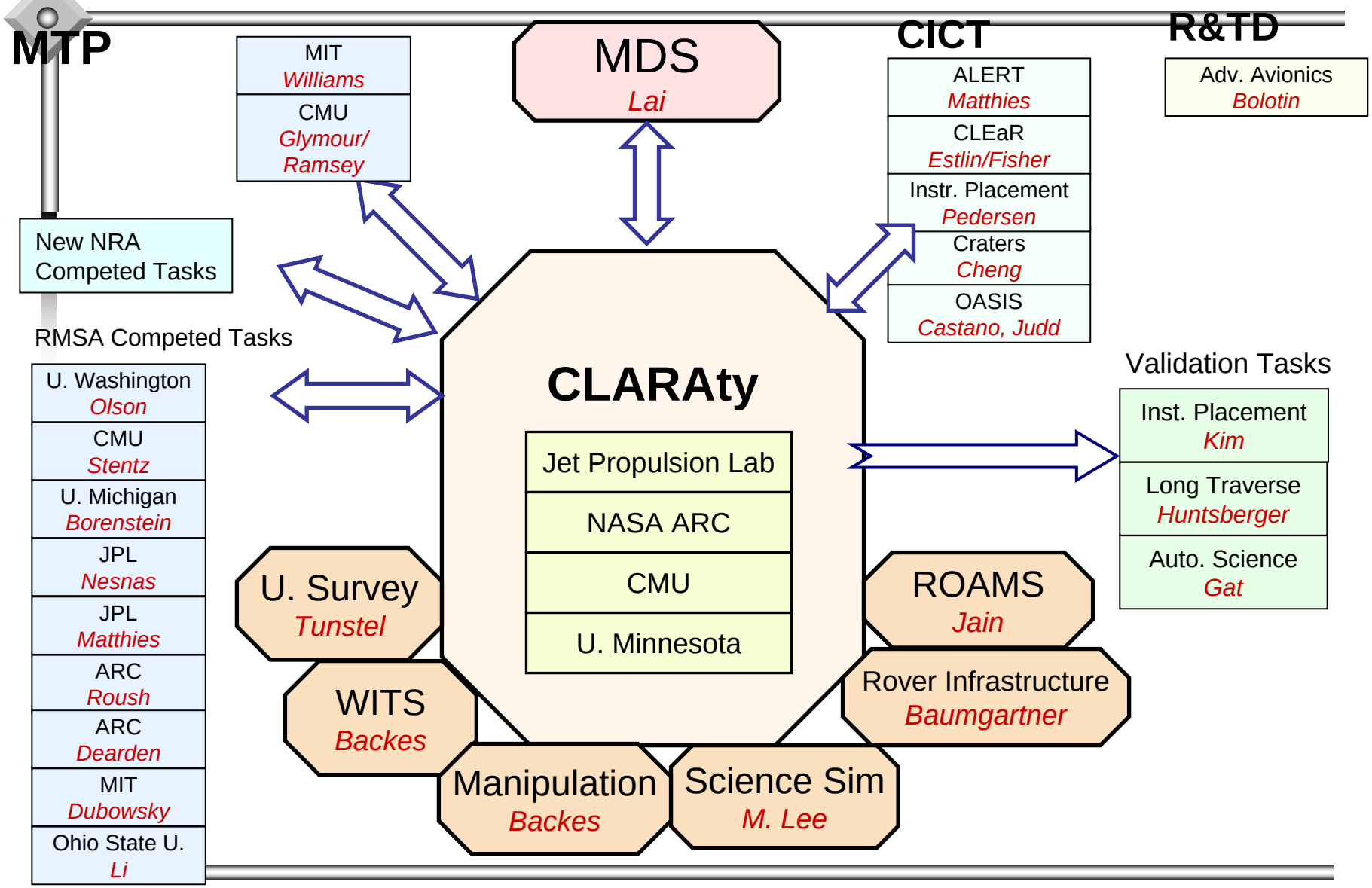
Summary

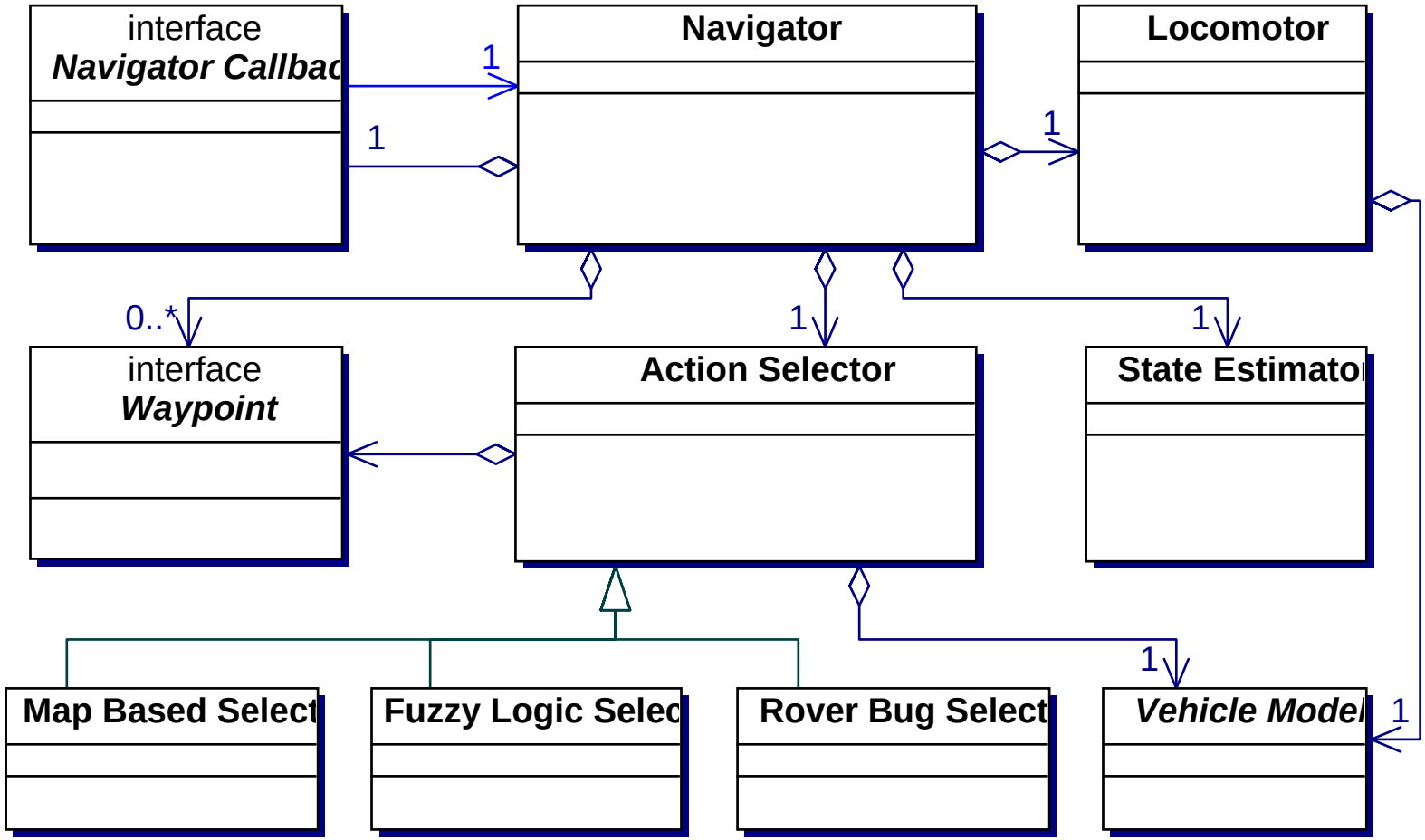
- CLARAty provides a repository of reusable software components at various abstraction levels
- It attempts at capturing well-known robot technologies in a basic framework for researchers
- It publishes the behavior and interfaces of its components
- It allows researchers to integrate novel technologies at different levels of the architecture
- It is a collaborative effort within the robotics community
- It will run on multiple heterogeneous robots

Component Analysis

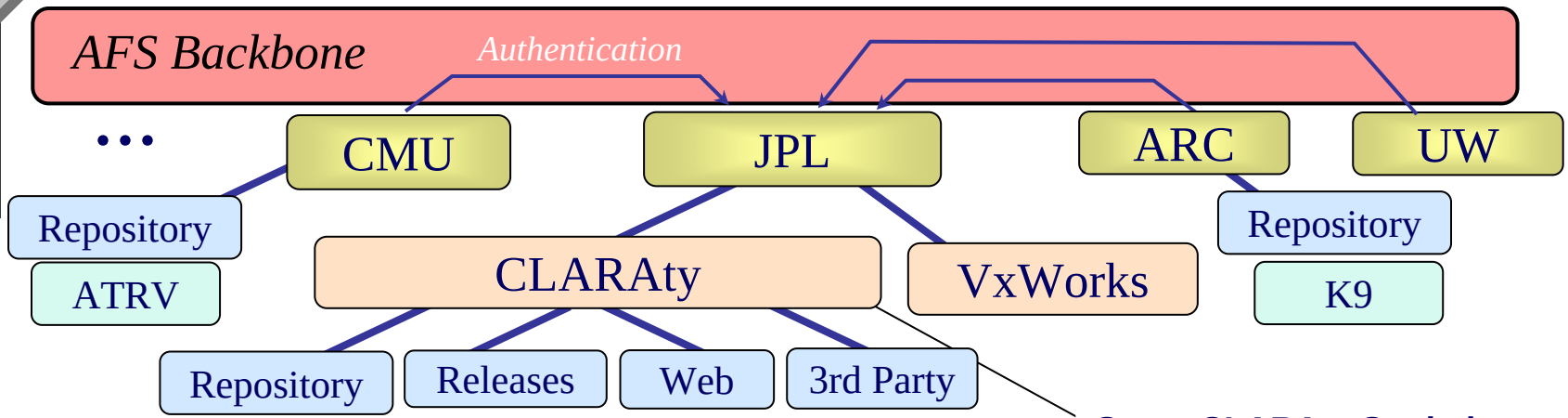


Collaborations



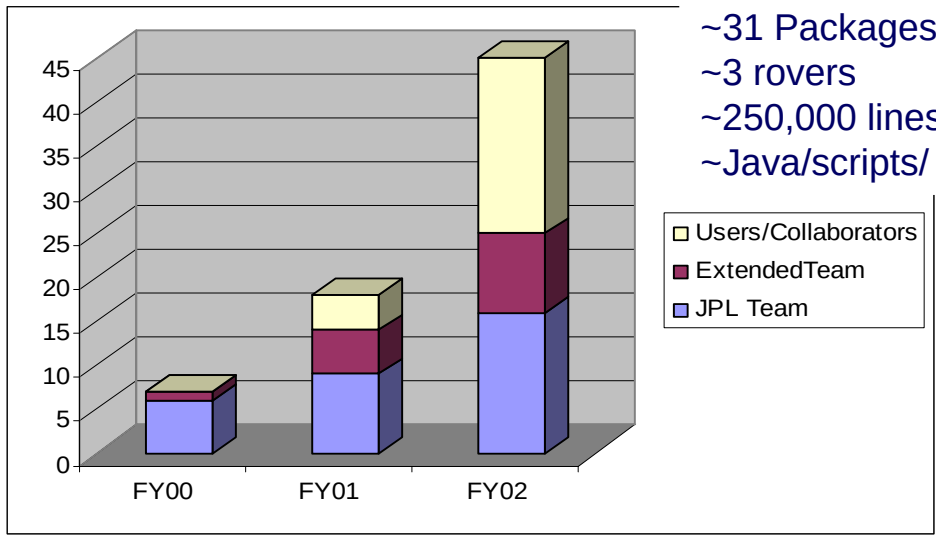

interface
Navigator Callbac
Navigator
Locomotor
1
1
1
0..*
1
1
interface
Waypoint
Action Selector
State Estimato
1
Map Based Select
Fuzzy Logic Selec
Rover Bug Select
Vehicle Model
1

Software Development Process



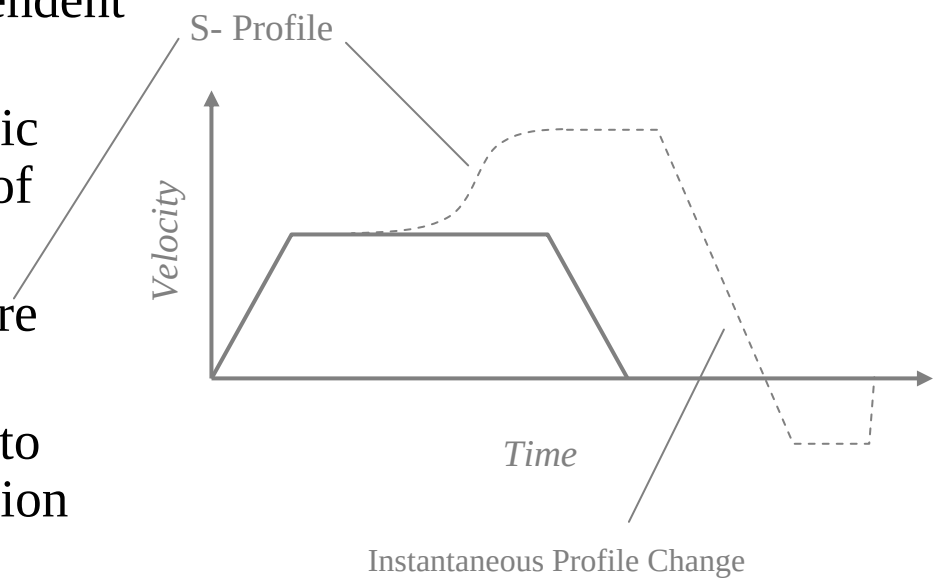
Some CLARAty Statistics

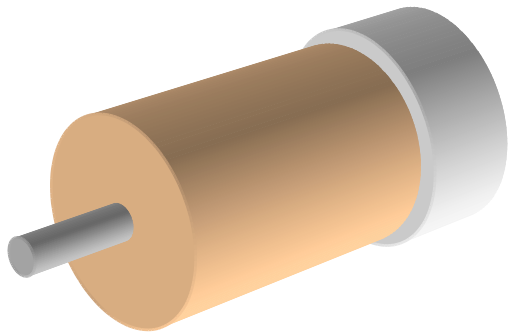
~170 Modules (reusable entity)
~31 Packages (module grps)
~3 rovers
~250,000 lines of C++ code
~Java/scripts/ and models



Example: Generic Controlled Motor

- Define generic capabilities independent of hardware
- Provide implementation for generic interfaces to the best capabilities of hardware
- Provide software simulation where hardware support is lacking
- Adapt functionality and interface to particular hardware by specialization inheritance
- Motor Example: public interface command groups:
  - Initialization and Setup
  - Motion and Trajectory
  - Queries
  - Monitors & Diagnostics





Example: collaborative development for locomotor

Version 1.0

- Designed for Rocky 7
- Used Motor class
- Separated wheel control from locomotion
- Built-in pose estimation

JPL - 1998

Redesign/ mature

Version 2.0

- Generalized design for wheeled locomotors
- Full and partially steerable vehicle
- Used generic motor classes
- Implements fixed axle model
- Developed continuous driving
- Adapted to Rocky 8, Rocky 7, and Sim

JPL - 2001

Redesign/ mature

Version 3.0

- Separated model from control
- Add separate locomotor state
- Add concept of wheel and steerable wheel, Drive Cmd, Drive Sequence
- Adapt to ATRV, Sim, Rocky 7, Rocky 8

CMU - 2002

Add

Version 4.0

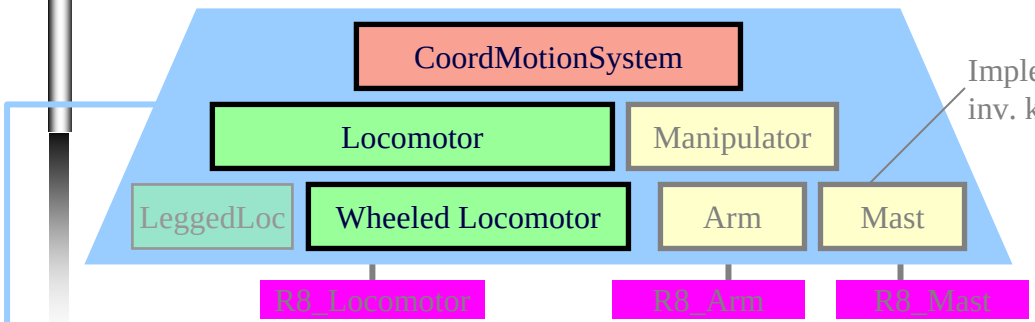
- Use device and telemetry infrastructure
  Add adaptation to K9

Future
ARC - 2003

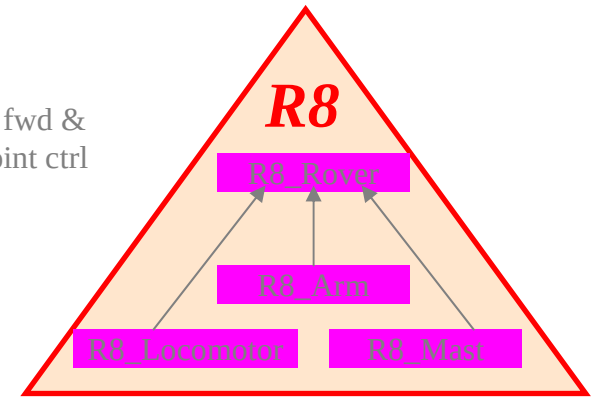
R8 Specific Rover Implementation

Non reusable Code

Reusable Code

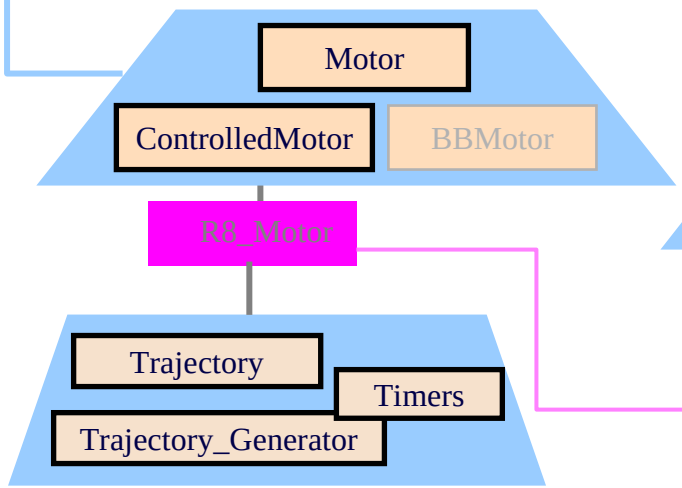


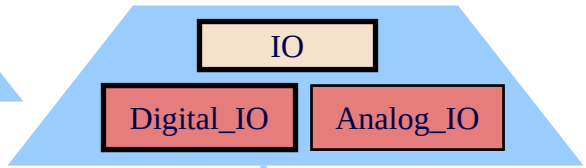
Implements general fwd & inv. kinematics & joint ctrl

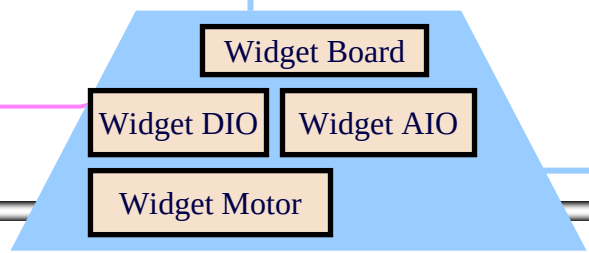


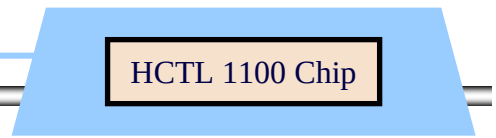
- Attaches proper motors
- Restricts Steering to 2 wheels

- Specialized inv. Kinematics (overrides default)
- Attaches proper motors
- Attaches proper cameras for mast
- Adds filter wheel









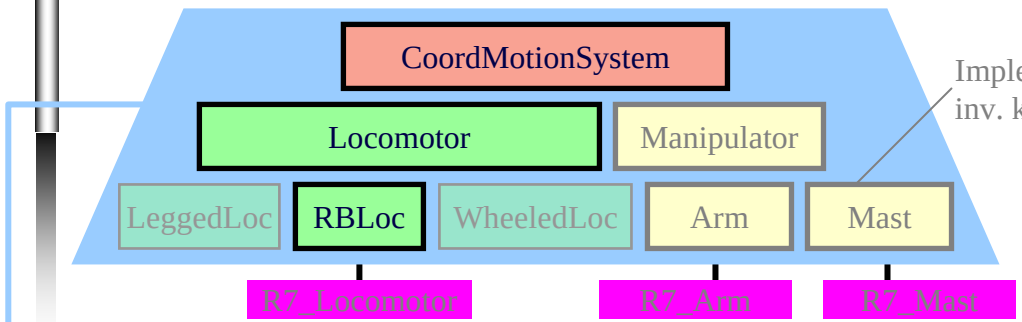
Capabilities of Wheel Locomotor

- Type of maneuvers:
  - Straight line motions (fwd / bkwd)
  - Crab maneuvers
  - Arc maneuvers
  - Arc crab maneuvers
  - Rotate-in-place maneuvers (arc turn r=0)
- Driving Operation
  - Non-blocking drive commands
  - Multi-threaded access to the Wheel_Locomotor class – e.g. one task can use Wheel_Locomotor for driving while the other for position queries
  - Querying capabilities during all modes of operation. Examples include position updates and state queries
  - Built-in rudimentary pose estimation that assumes vehicle follows commanded motion

R7 Specific Rover Implementation

Non reusable Code

Reusable Code



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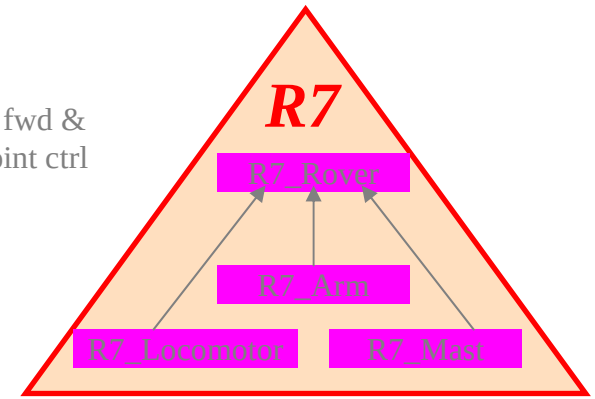

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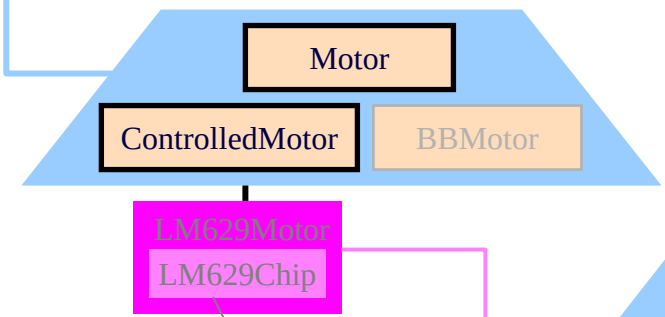

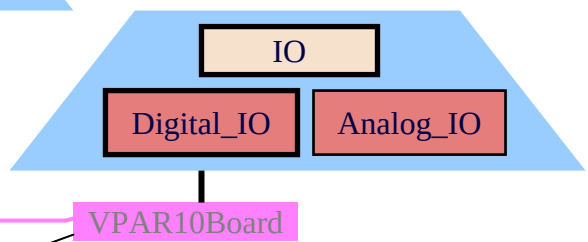

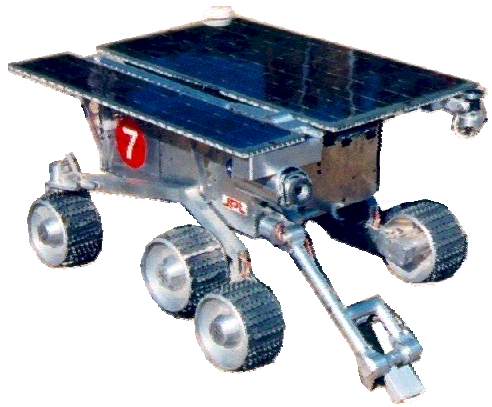

Device Drivers

Why is robotic software “hard”?

- Software:
  - Software is large and complex
  - Has lots of diverse functionality
  - Integrates many disciplines
  - Requires real-time runtime performance
  - Talks to hardware
- Hardware:
  - Physical and mechanics are different
  - Electrical hardware architecture changes
  - Hardware component capabilities vary

What is CLARAty?

CLARAty is a *unified* and *reusable* **software** that provides robotic functionality and simplifies the integration of new technologies on robotic platforms

A research tool for technology development and maturation