CLARAty: Improving Software Reliability for Robotic Space Applications

Coupled Layer Architecture for Robotic Autonomy

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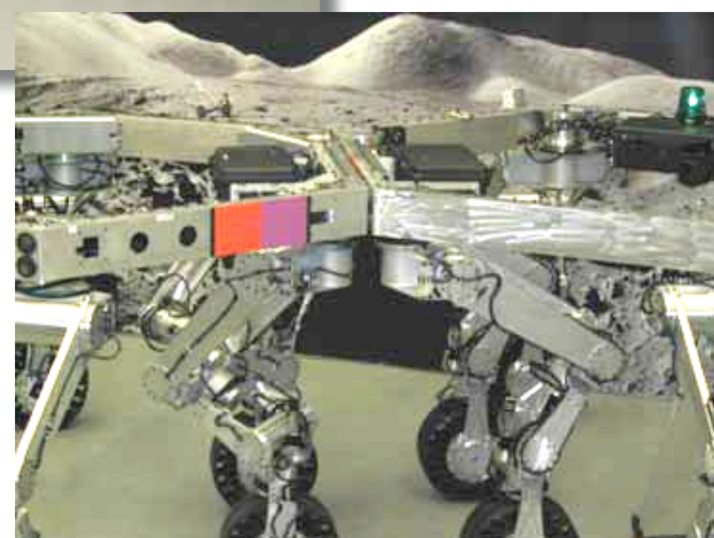
Presentation Overview

- Historical Antecedents
- Application Domains
- Techniques used to Improve Reliability
  - Rigorous Process
  - Software Reuse
  - Formal Validation
  - Continuous Automated Testing
- Challenges for Software Reuse and Interoperability
- Challenges in Technology Infusion

Some JPL Robots / Rovers

More Robots



Historical Antecedents

- **Late 80's - Early 90's:** parallel robotic developments
  - RSI, MOTES, Satellite Servicing, Robby, Mircorover
  - No shared *hardware* or *software*
- **Mid 90's:** Mars rover research centralized with Rocky 7
  - First flight rover
- **Late 90's:** Expansion and diversification of rover work
  - No software interoperability (Rocky 7, FIDO, Athena, DARPA)
  - Autonomy demonstration of Remote Agent Experiment (ARC and JPL)
  - MDS investigates reusable software for spacecraft control.
- **'99-Early 00:** Exploration Technology Program develops concept for a unifying autonomy architecture
  - Unifying autonomy and robotic control
  - Started the CLARAty task
- **Today:**
  - Unification of several robotic developments at JPL, ARC, and CMU
  - Two flight rovers with several new robotic capabilities

Application Domains

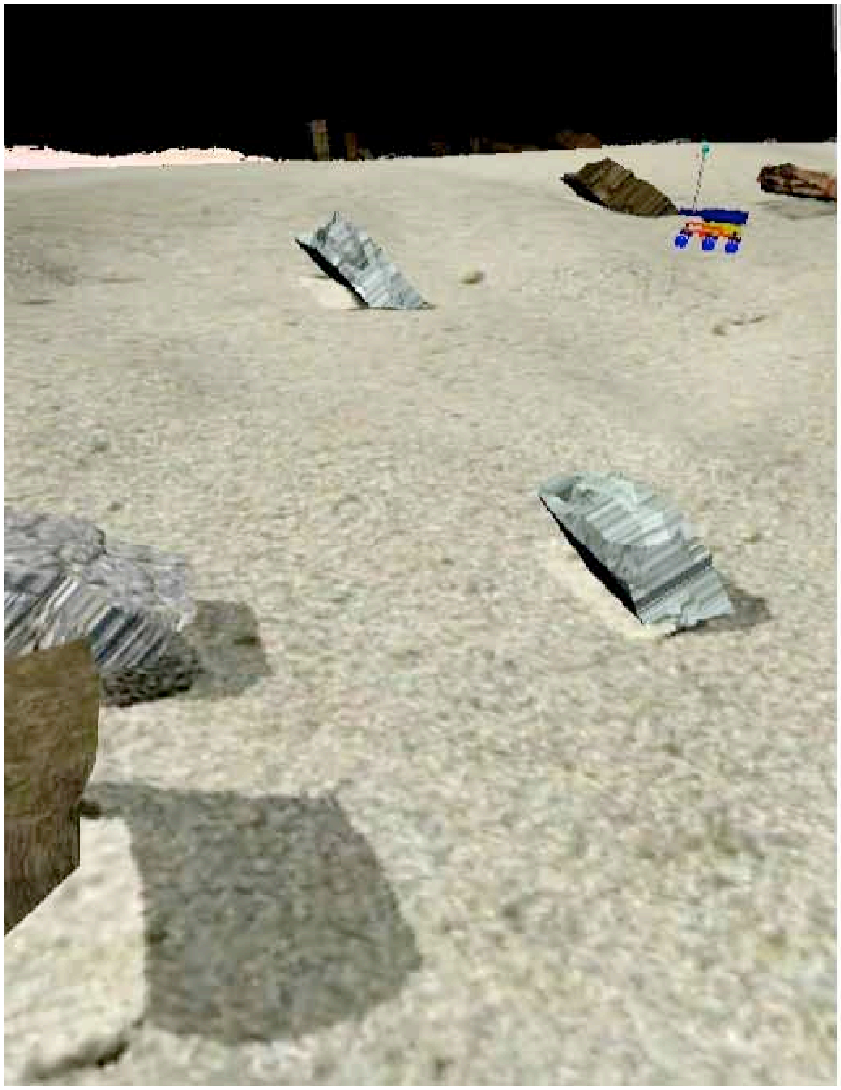
- Navigation
- Target Tracking
- Single-cycle Instrument Placement

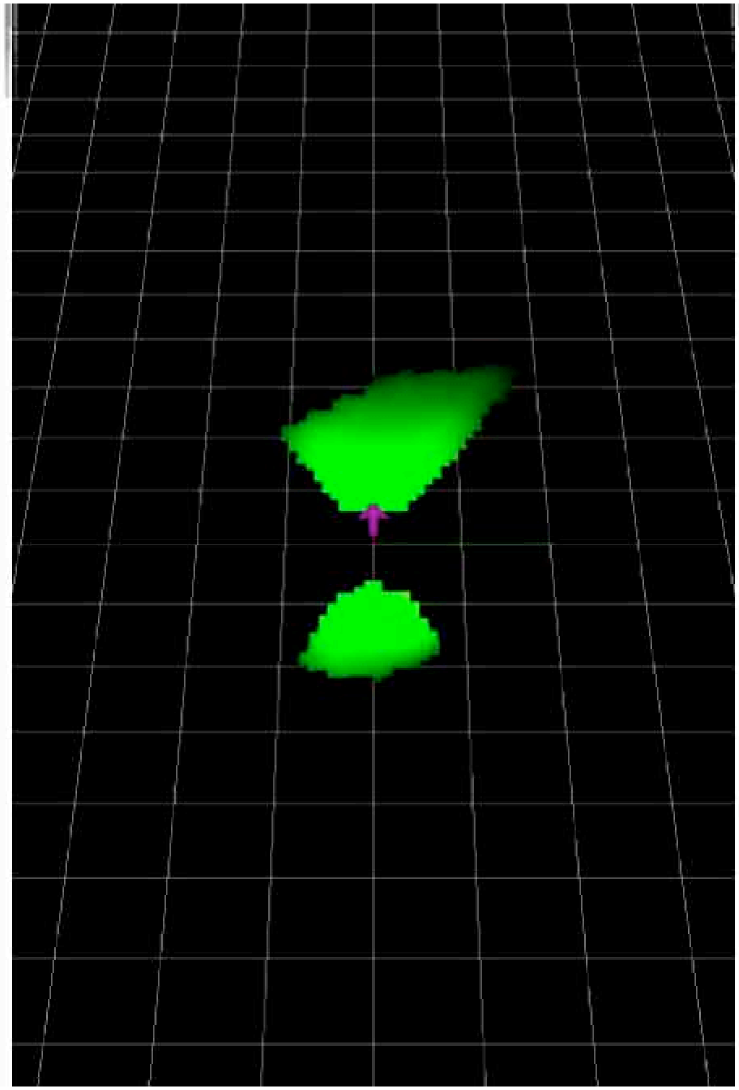
Navigation with Different Rovers

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

Navigation with Dynamic Simulator





Application Domains

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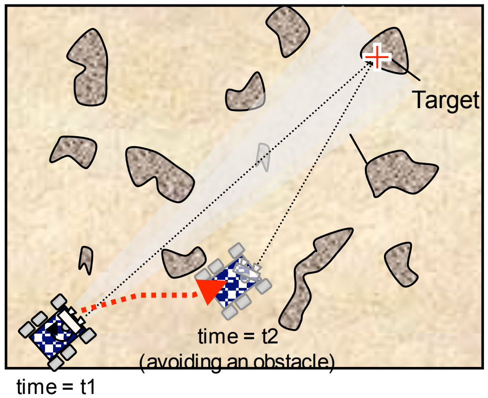
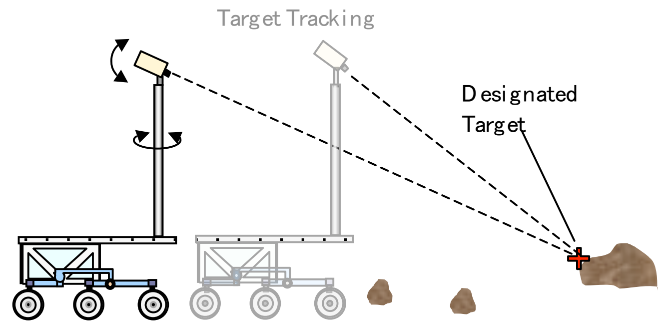
Visual Target Tracking



(a)



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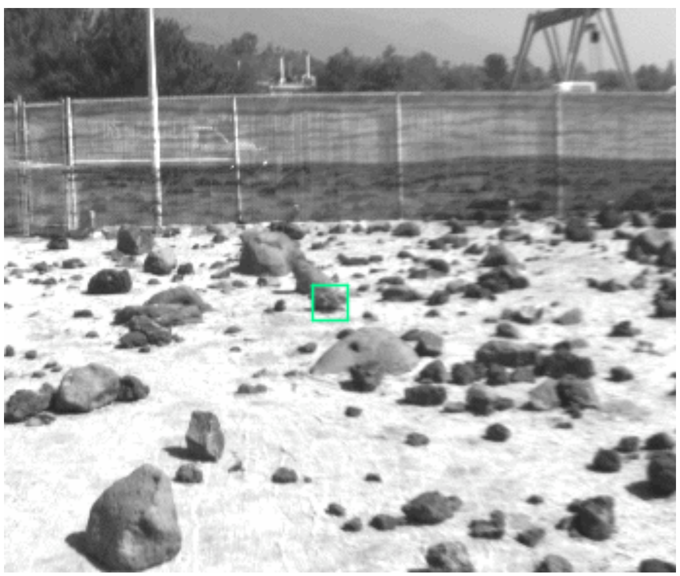
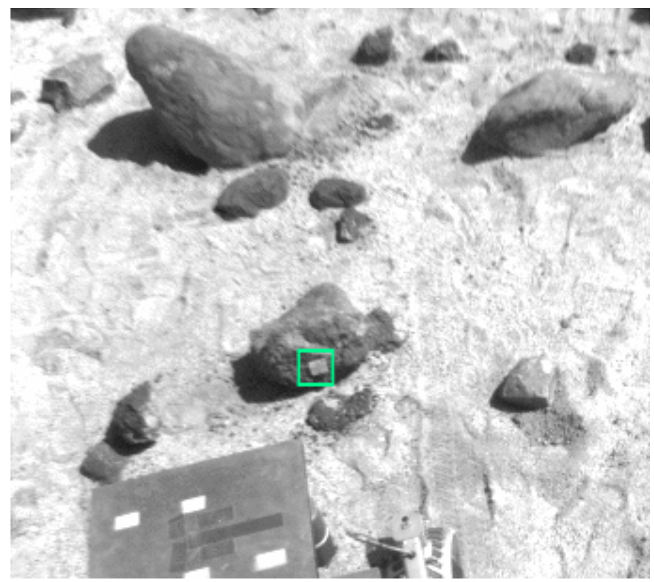


1^{st} Frame

Changes in FOV



37^{th} Frame after 10 m

FALCON Visual Target Tracker on Rocky 8

Application Domains

- Navigation
- Target Tracking
- Single-cycle Instrument Placement

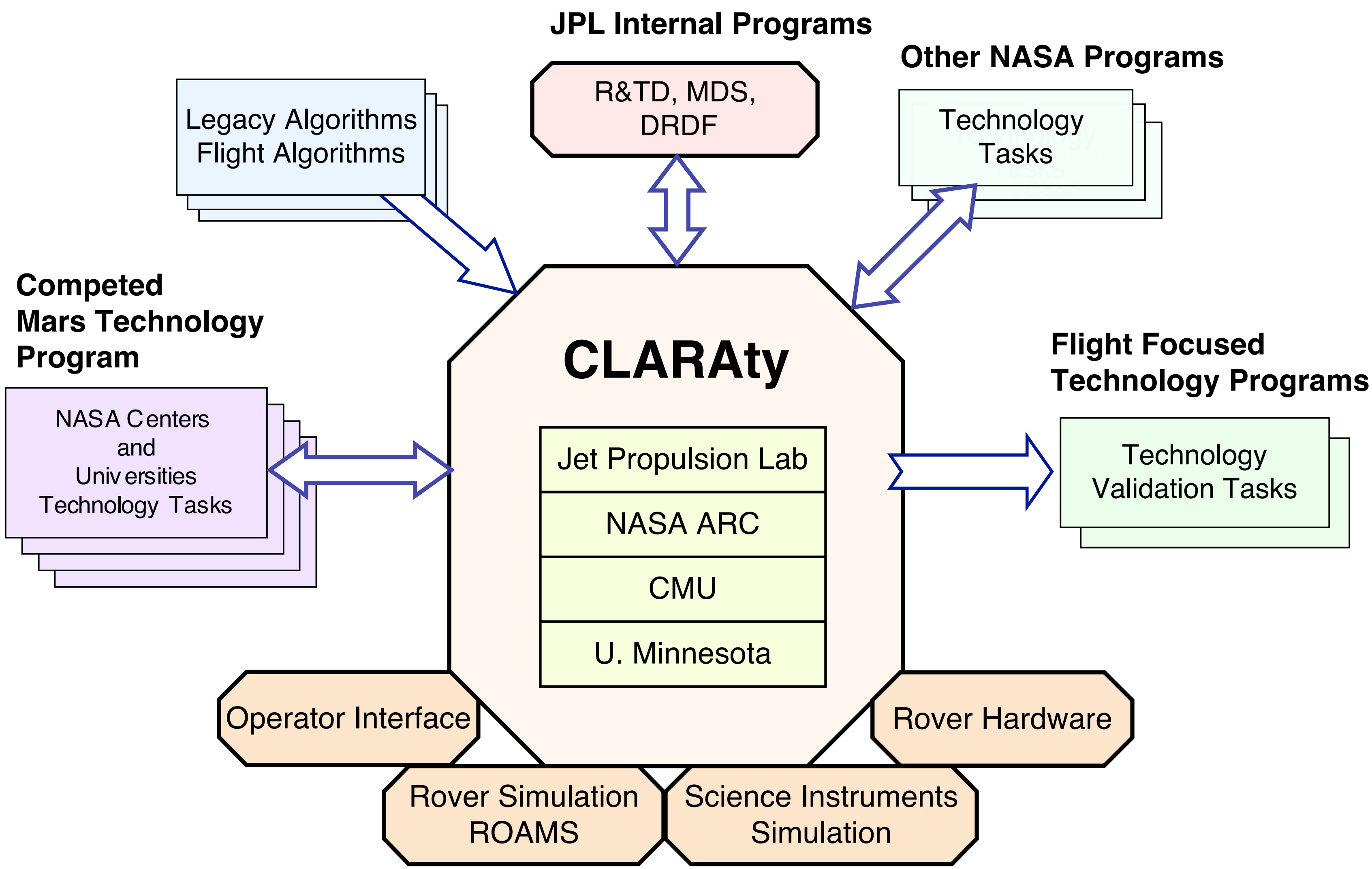
Integrated Single-Cycle Instrument Placement

Techniques We Use

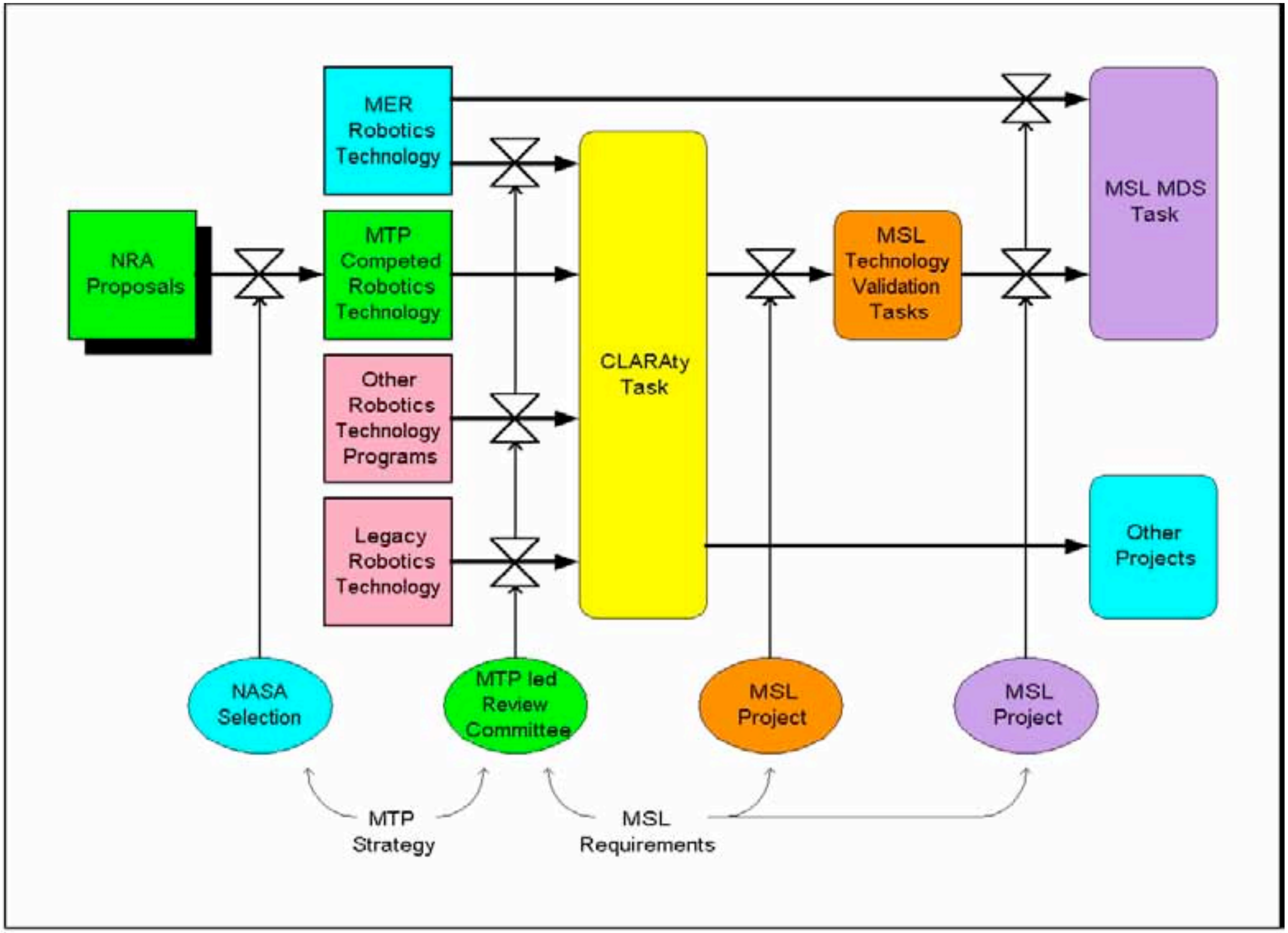
- Some of the techniques that we have explored to improving software reliability are:
  - Improved processes and procedures for software development
  - Static code analysis and validation tools
  - Increased software reliability through reuse
  - Formal technology validation
  - Nightly regression testing
  - Fault-tolerant software and redundant computing

Process

Technology Development, Integration and Validation



Technology Component Flow



Flight Software Processes and Tools

- List coding conventions, rules, and guidelines.
- Use only mission-proven or thoroughly tested technologies
- Hold formal design reviews
  - Review designs before and after implementation
  - Review interfaces, implementations, test plans, commands, and telemetry for each software component
- Use code buddy reviews
  - Have someone other than the developer statically review the code and look for potential problems or violations of the coding conventions.
  - Use automated tools for source code analysis to highlight suspicious code segments. For example, MER used Code Wizard and Cleanscape on early versions of the flight software and Coverity on most recent versions.
  - Review by internal and external teams. Use validation and verification group expertise.

Rigorous Flight Software Testing

- Unit Testing:
  - Extensive testing of each module in isolation by the developer
- Regression Testing:
  - Integrated module testing by a dedicated test team after new modules are integrated.
- System Testing:
  - Project wide rehearsals of expected mission scenarios
  - Can last several days where several different activities would be tested in the manner they would be used in the mission.
  - All communication is done during communication passes.

Flight Software Architecture and Implementation

- Assignment of one "owner" developer per software module
- Object-oriented style design, with emphasis placed on interfaces, encapsulation, and modularity
- Objects implemented as hierarchical state machines
- Asynchronous message passing as the principle means of communication between objects
- Severe limitations on use of dynamic memory allocation to avoid heap fragmentation
- Extensive use of diagnostics embedded throughout the software, including many design-by-contract assertions
- Reference:
  - Glenn E. Reeves & Joseph F. Snyder "A Overview of the Mars Exploration Rovers' Flight Software" 2005 IEEE International Conference on Systems, Man and Cybernetics Waikoloa, Hawaii, October 10-12, 2005

Historical Antecedents and Motivation

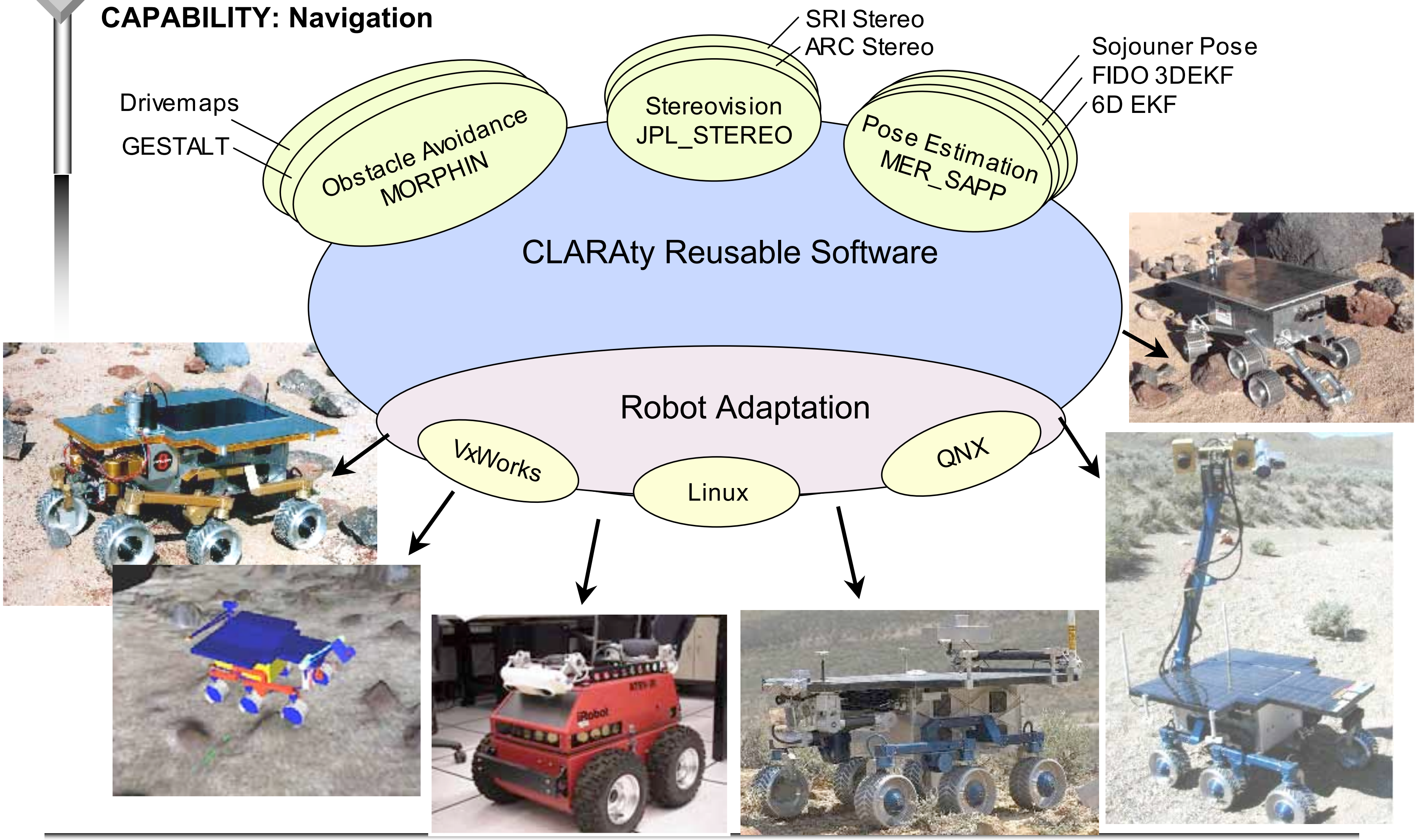
Problem and Approach

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

- Objectives
  - Unify robotic infrastructure and framework
  - Capture and integrate legacy algorithms
  - Simplify integration of new technology
  - Operate heterogeneous robots

Interoperability: Software & Hardware

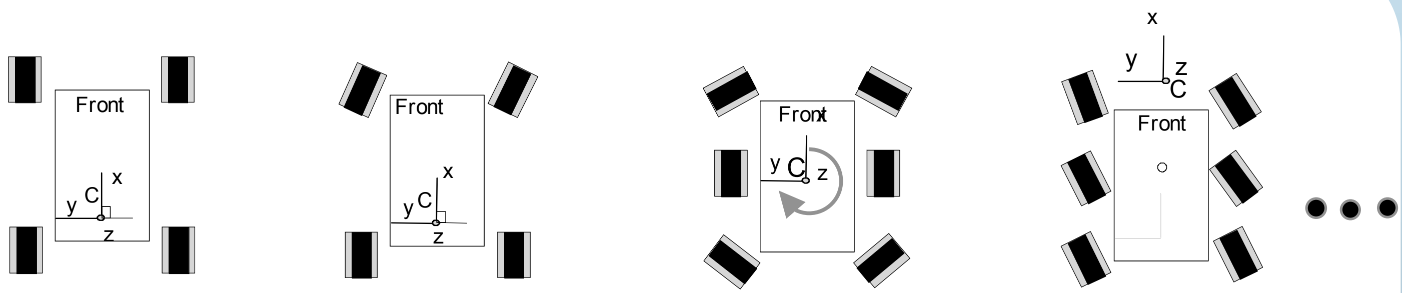
CAPABILITY: Navigation



Challenges in Reuse

- Mechanisms and Sensors
- Hardware Architecture
- Software Algorithms

Different Mobility Mechanisms



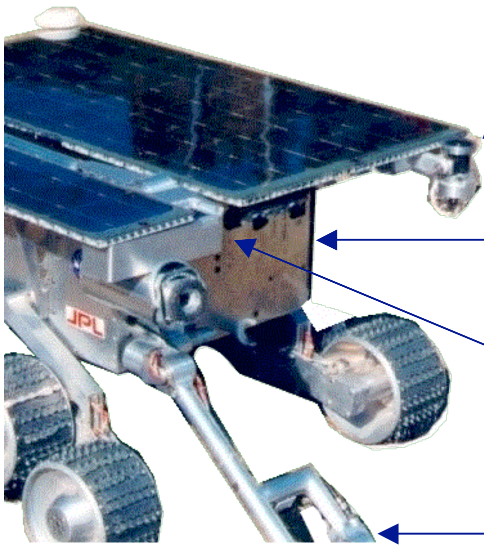
(a)
Skid Steering
(no steering wheels)

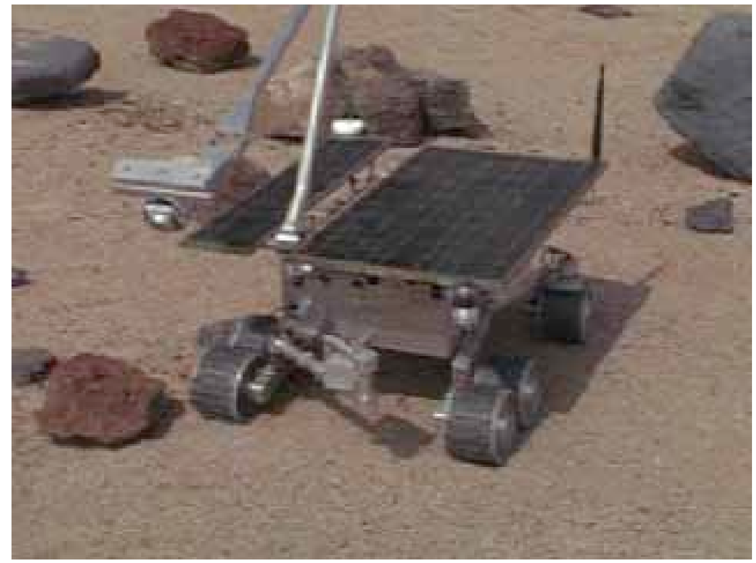
(b)
Two –wheel steering

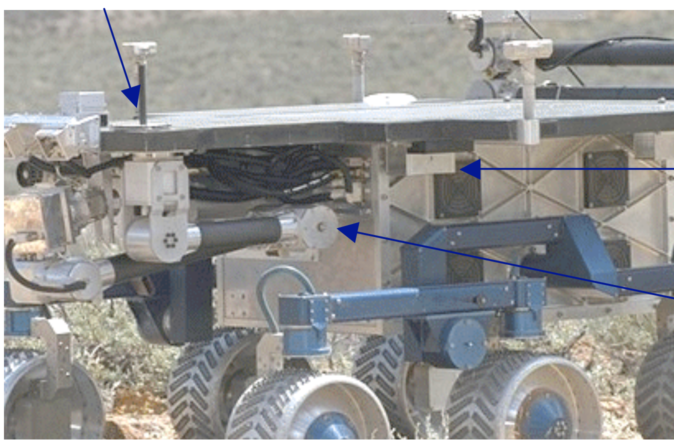
(d)
Partially Steerable
(e.g. MER, Sojourner, Rocky 7)

(e)
All wheel steering
(e.g. Rocky8, FIDO, K9)

Different Sensors and Appendages





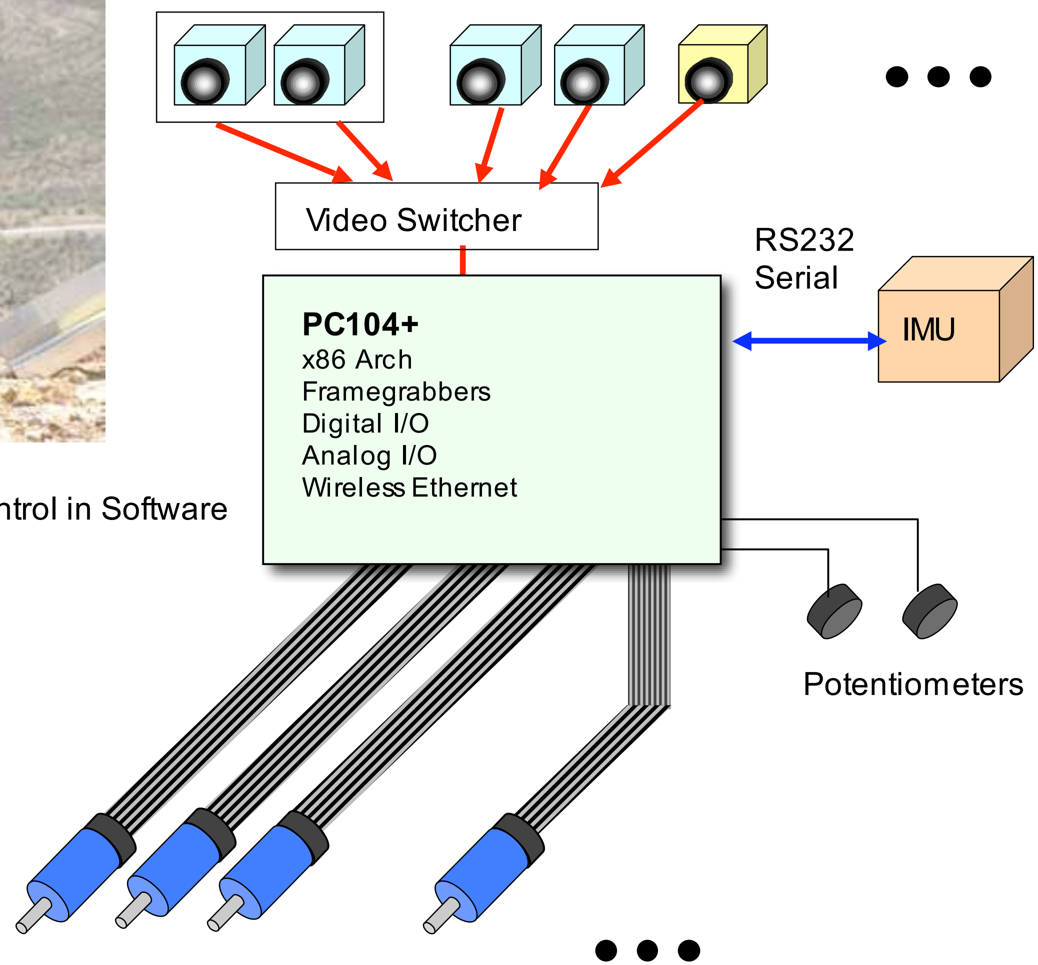


Challenges in Reuse

- Mechanisms and Sensors
- Hardware Architecture
- Software Algorithms

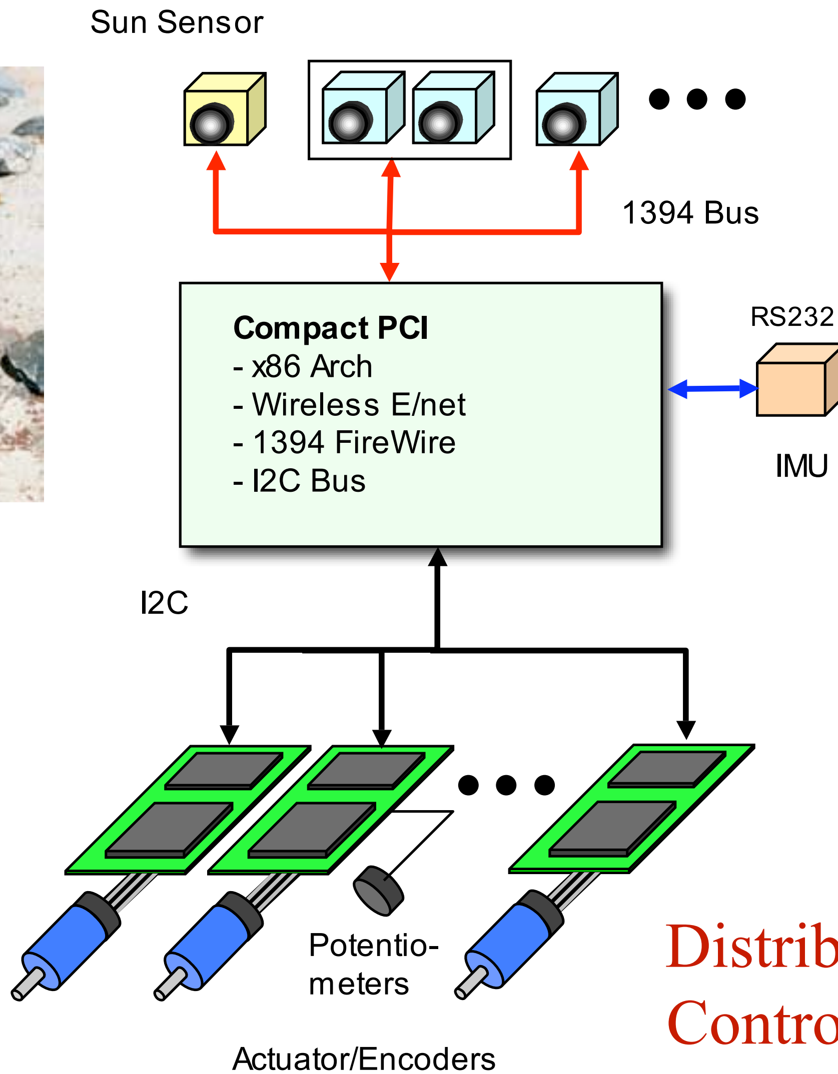
Centralized Hardware Architecture

FIDO



Distributed Hardware Architecture

Rocky 8



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

Distributed Motion Control and Vision

Challenges in Interoperability

- Mechanisms and Sensors
- Hardware Architecture
- Software Algorithms

Software Challenges for Algorithm Infusion

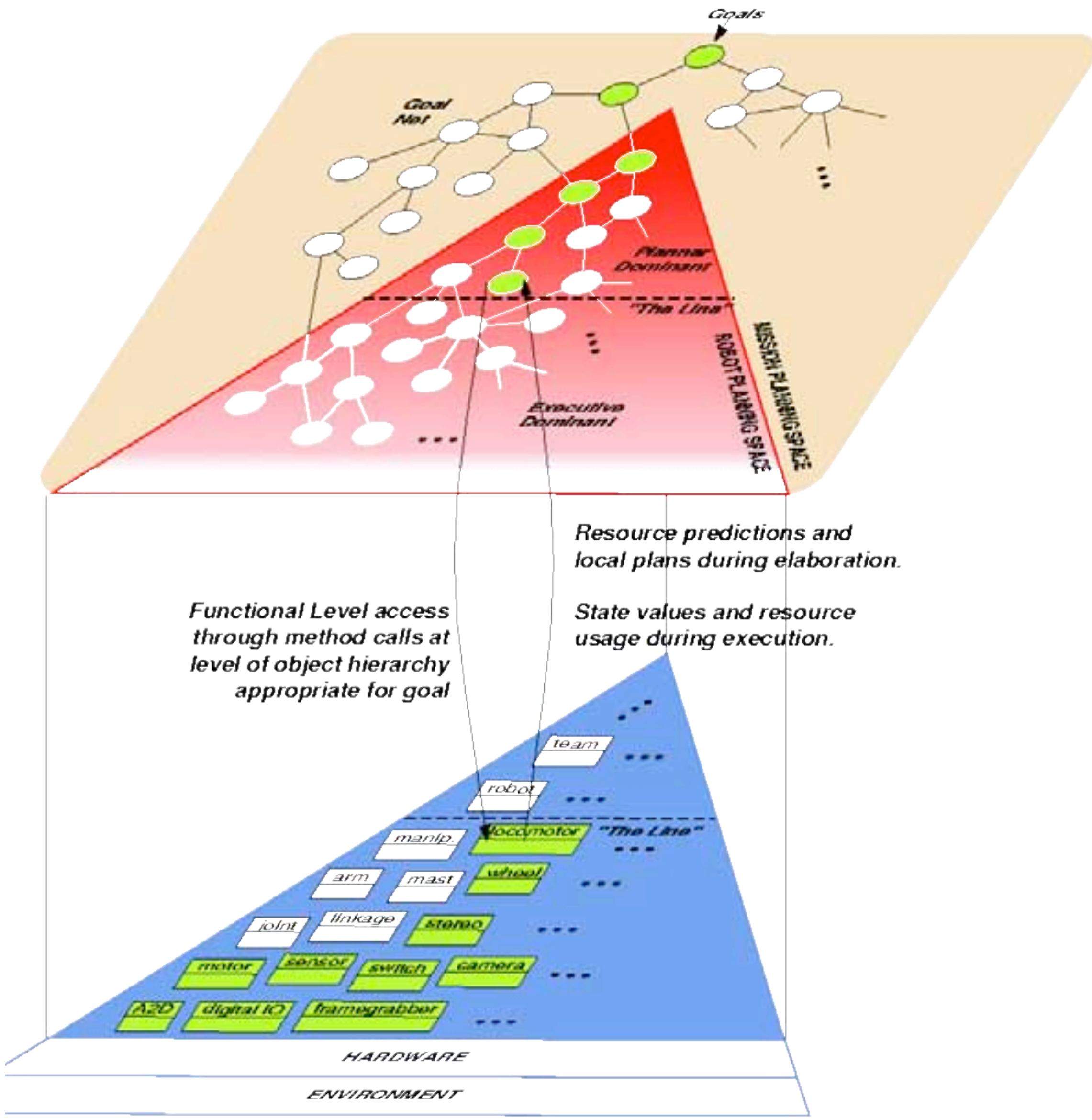
The *new* algorithms to be integrated may:

- Have architectural mismatches with the framework
- Include multiple orthogonal functionalities
- Make implicit assumptions about the platform
- Duplicate functionality in the framework
- Use incompatible data structures
- Are complex and hard to tune
- Require highly specialized domain expertise
- Are poorly implemented

Architecture and Process

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:

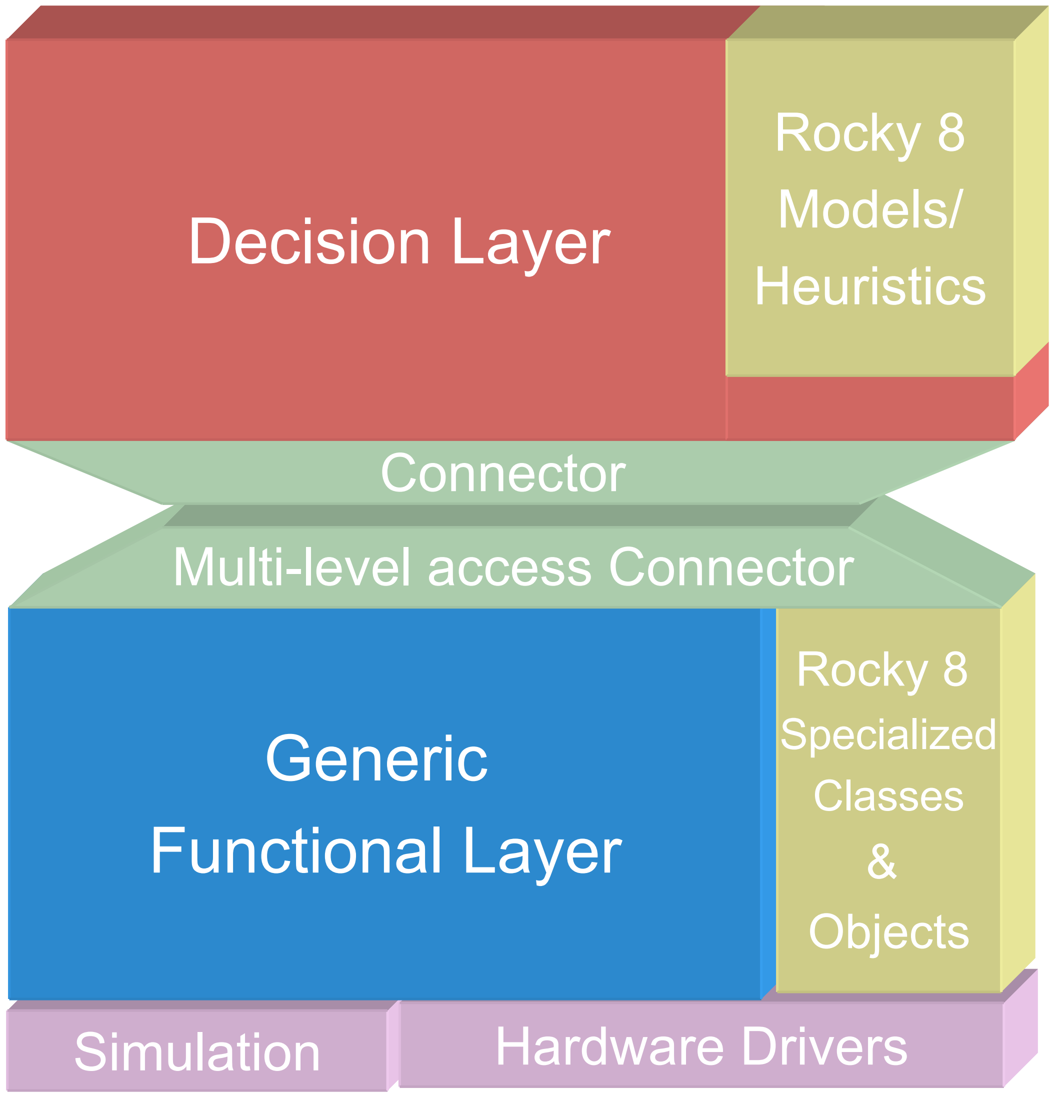
Object-oriented abstractions

Autonomous behavior

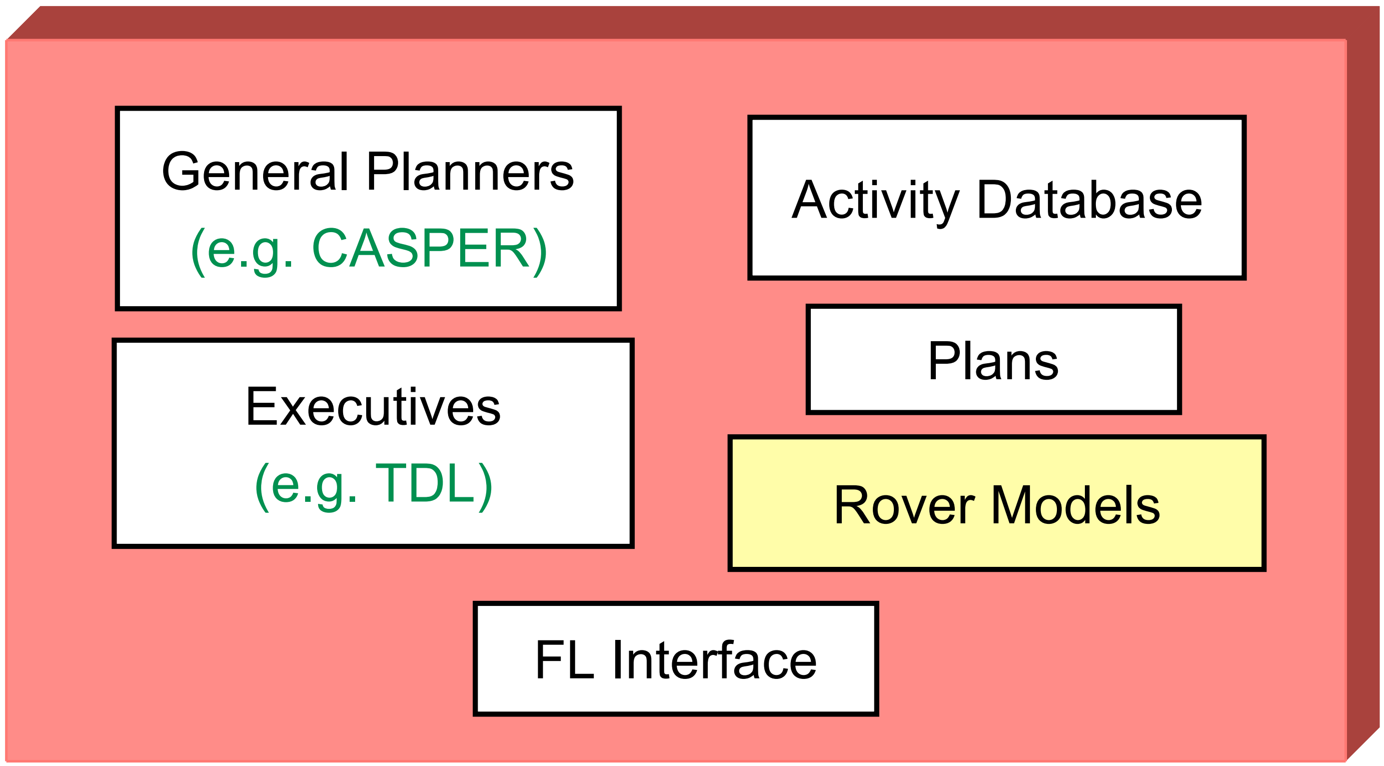
Basic system functionality

Adaptation to a system

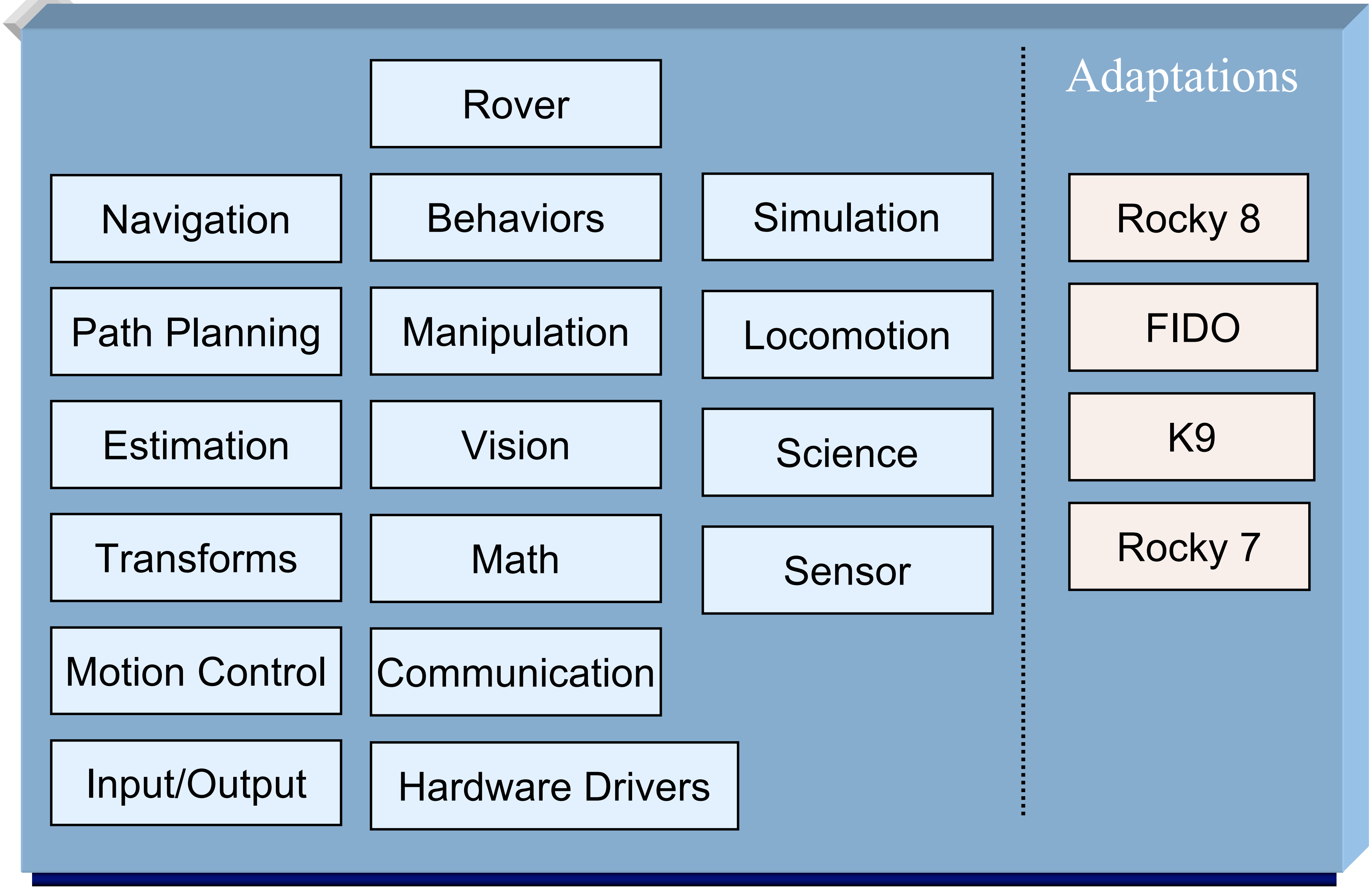
Adapting to a Rover



The Decision Layer

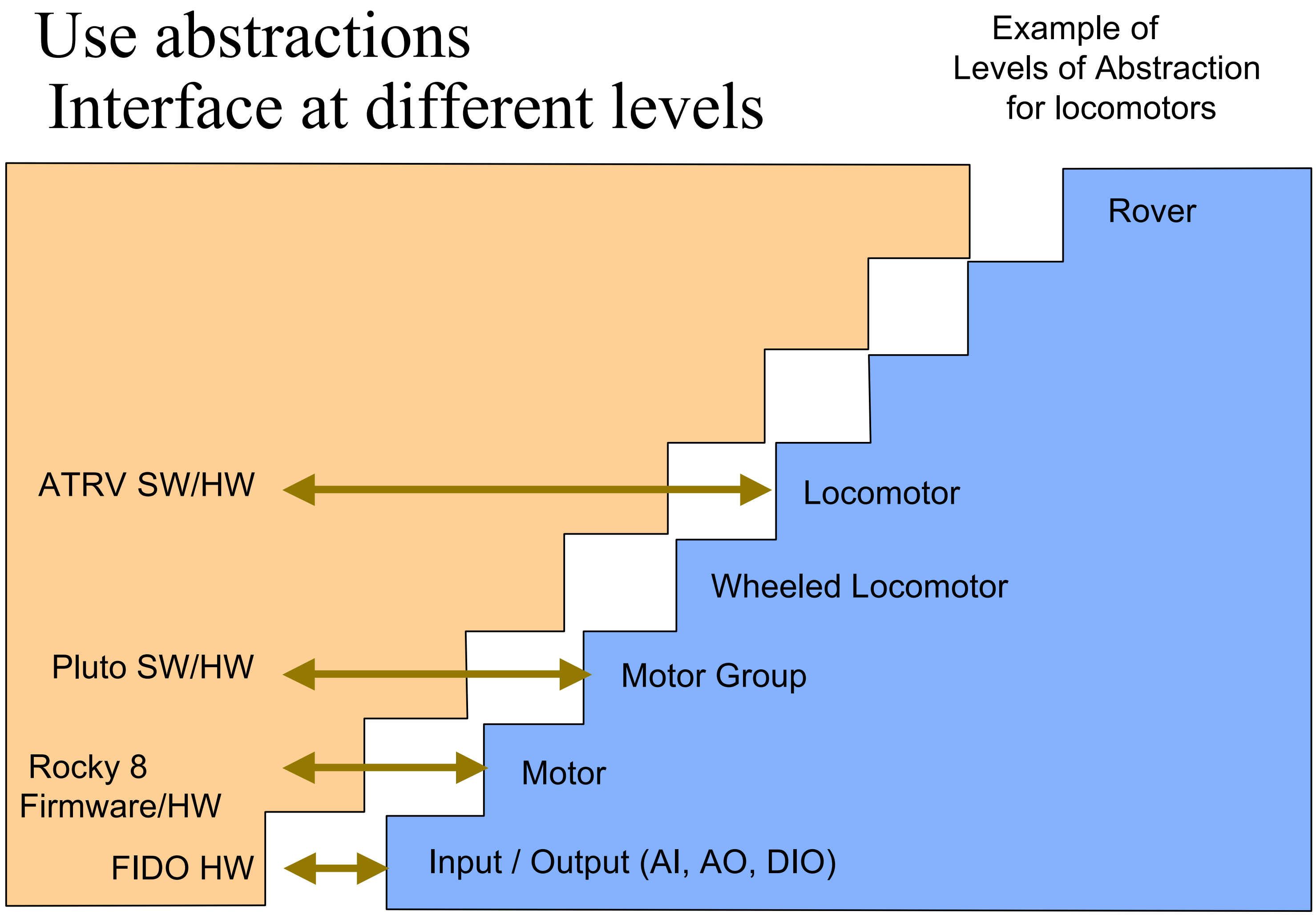


The Functional Layer

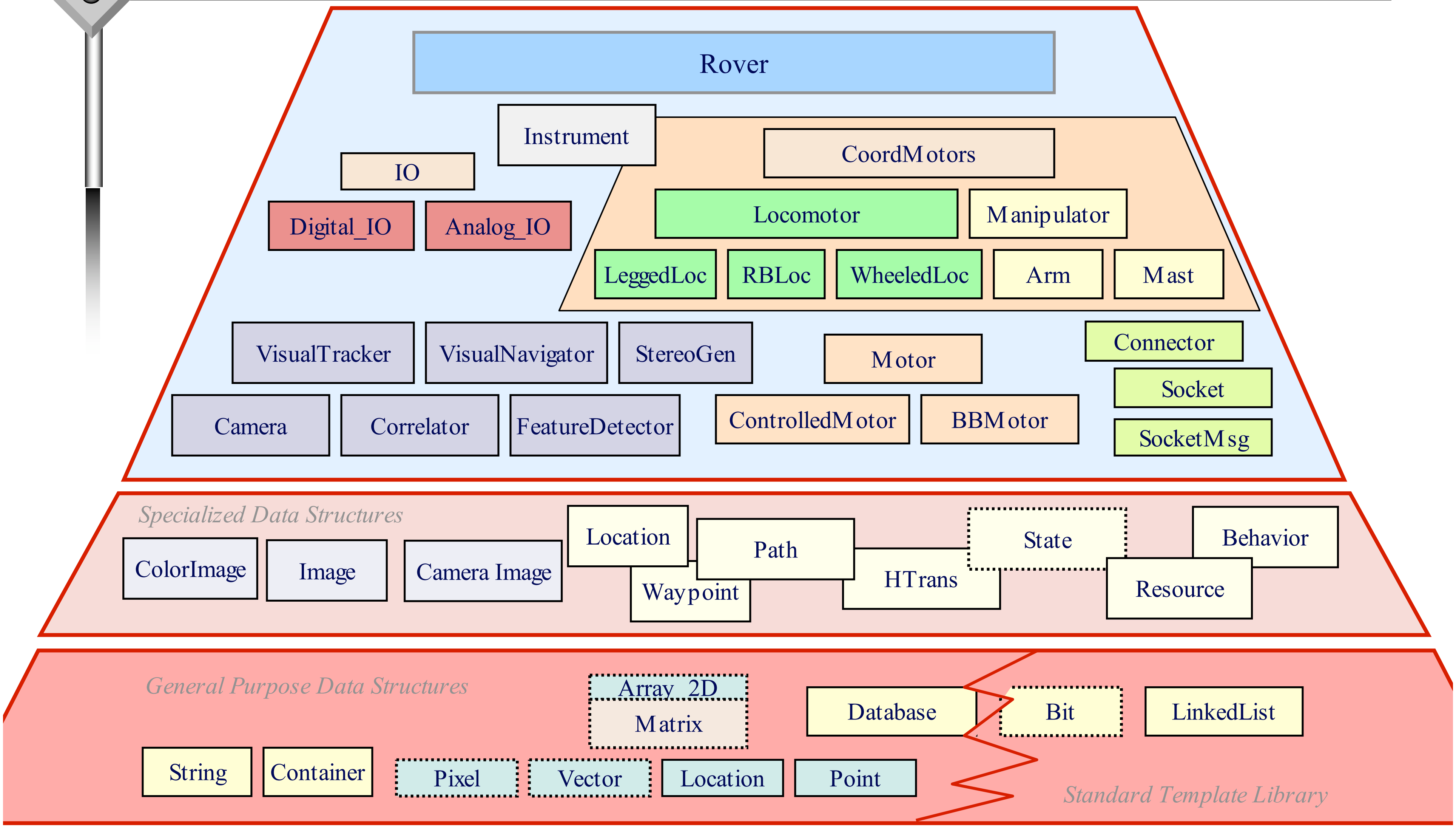


Multi-level Abstraction Model

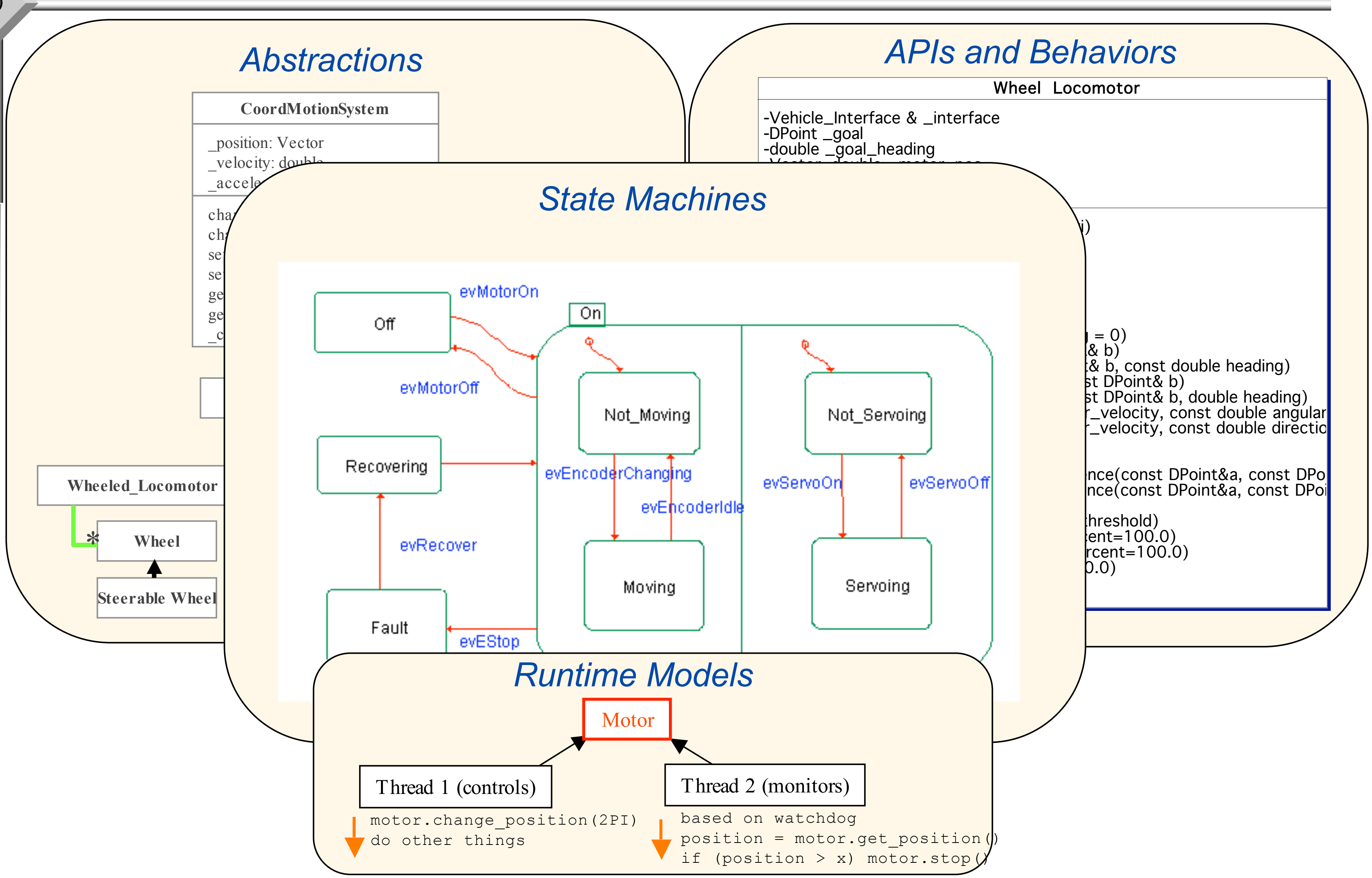
Use abstractions
Interface at different levels



Functional Layer Components

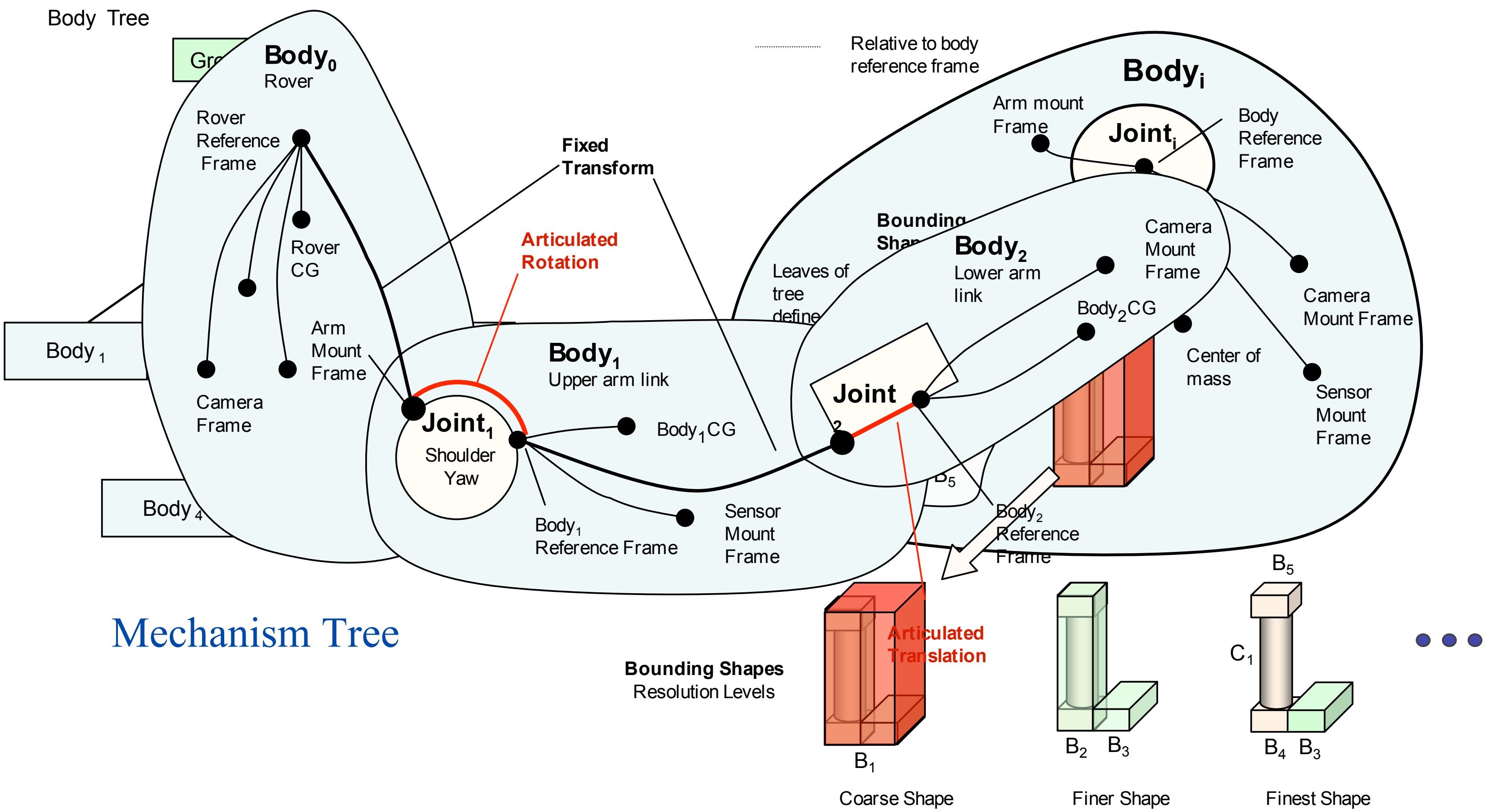


Standardizing Base Abstractions



Unify Mechanism Model

Bodies and Joints



Mechanism Tree

Unit and Regression Testing

CLARAty Test Bed for Regression Testing

FIDO2 Stack

ATRV Jr.

Dexter Manipulator
Bench top

Rocky 8 PPC Bench top

Summary

- Software complexity and size continues to rise
- Increasing software reliability remains a challenge because algorithms are sensitive to environmental uncertainties
- Formal validation of algorithms helps assess performance and risk of technology
- Reuse of framework helps improve reliability of infrastructure
- Deploying at multiple institutions and on heterogeneous robots improves reliability through diversity
- Assessing performance and risk is critical for infusion into flight

Current CLARAty Core Team

- **NASA Ames Research Center**
  - Clay Kunz
  - Eric Park
  - Susan Lee
- **Carnegie Mellon University**
  - David Apelfaum
  - Nick Melchior
  - Reid Simmons
- **University of Minnesota**
  - Stergios Roumeliotis
- **Jet Propulsion Laboratory**
  - Antonio Diaz Calderon
  - Tara Estlin
  - John Guineau
  - Won Soo Kim
  - Richard Madison
  - Michael McHenry
  - Mihail Pivtoraiko
  - Issa A.D. Nesnas
  - Babak Sapir
  - I-hsiang Shu
- **OphirTech**
  - Hari Das Nayar

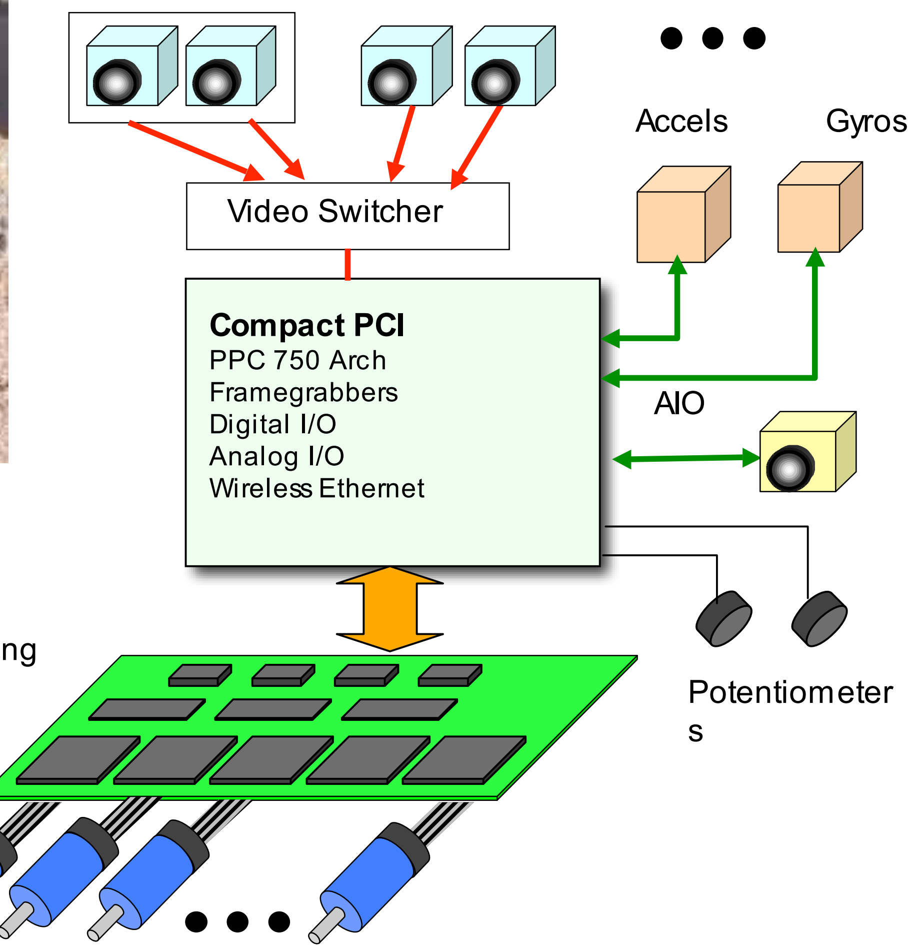
Full Credits for all Developers and Contributors at:
http://keuka.jpl.nasa.gov/main/project/team/index.shtml

Thank you

Back-up Slides

Semi-centralized Hardware Architecture

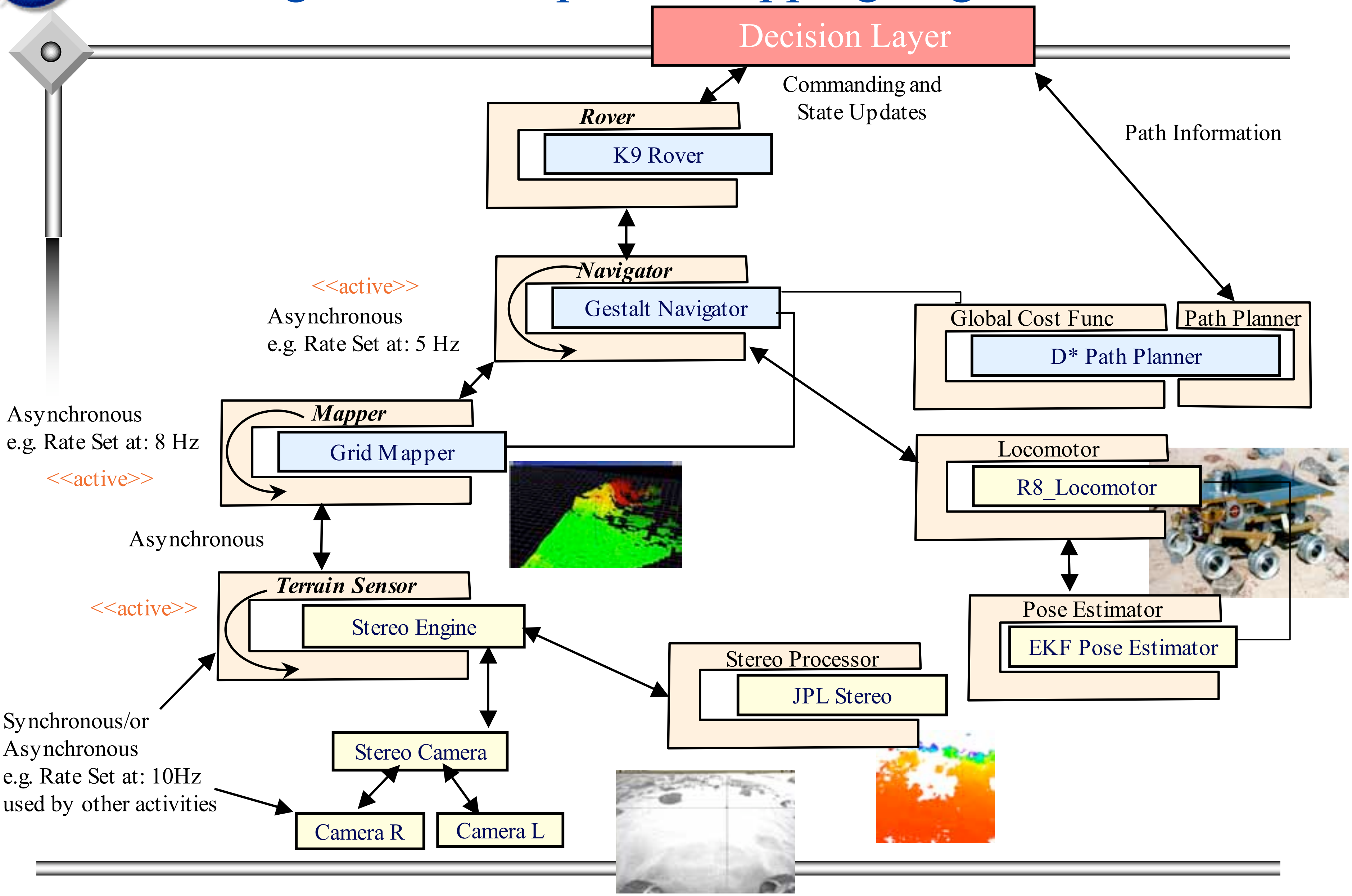
Rocky 7



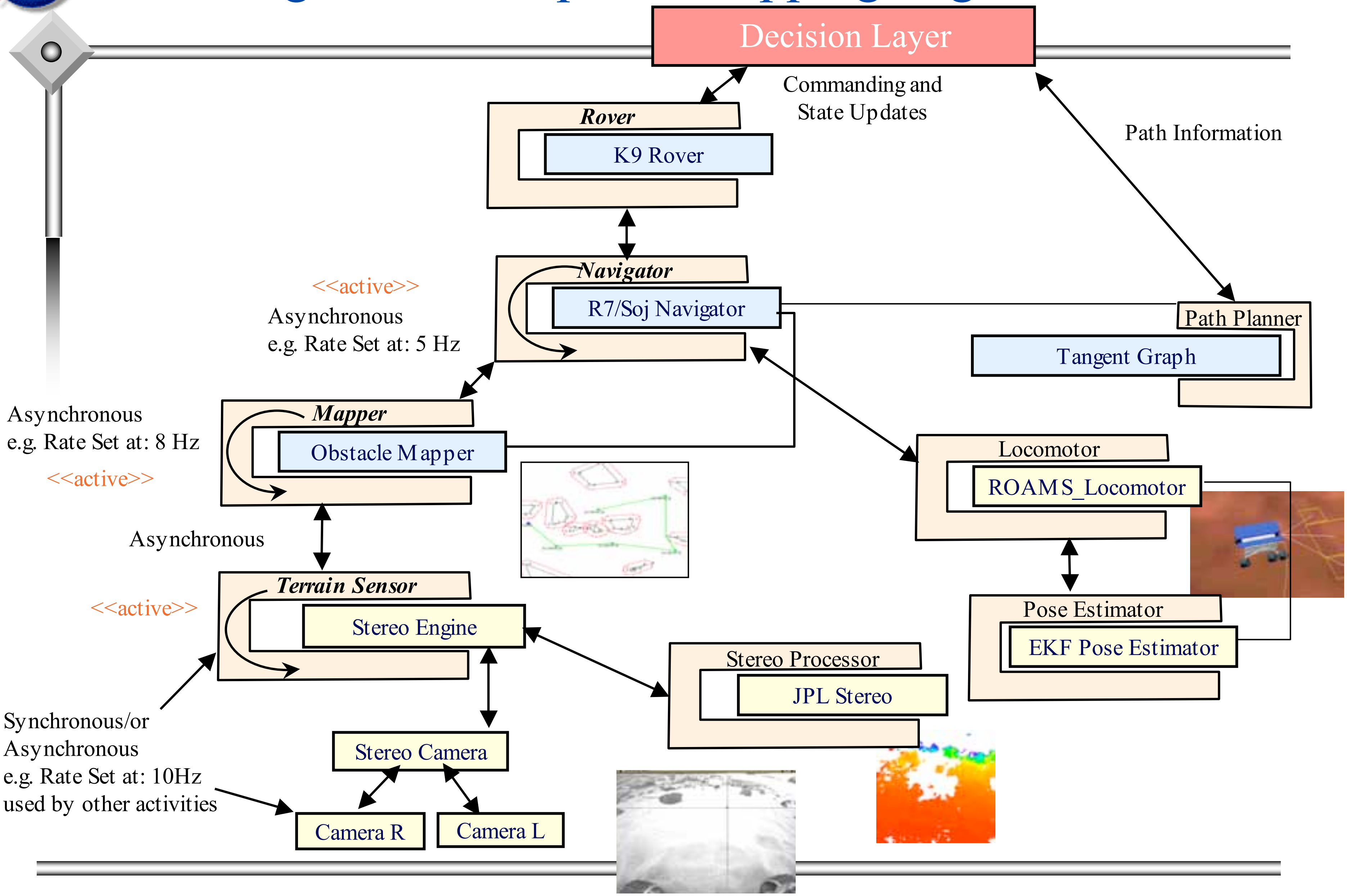
One Approach

- Develop
  - Common data structures
  - Physical & Functional Abstractions
    - E.g. motor, camera, locomotor. Stereo processor, visual tracker
  - Unified models for the mechanism
- Putting it together
  - Start with top level goals
  - Elaborate to fine sub-goals
  - Choose the appropriate level to stop elaboration
  - Interface with abstractions
  - Abstractions translate goals to action
  - Specialize abstractions to talk to hardware
  - Hardware controls the systems and provide feedback

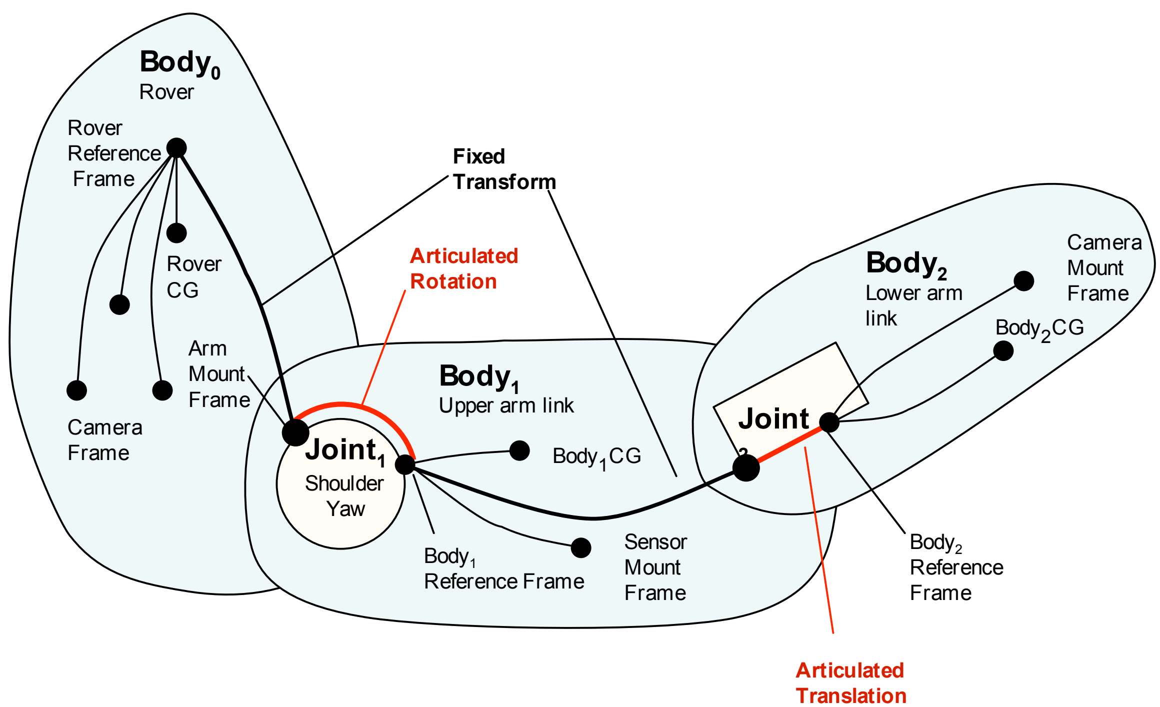
Navigation Example - Swapping Algorithms



Navigation Example - Swapping Algorithms



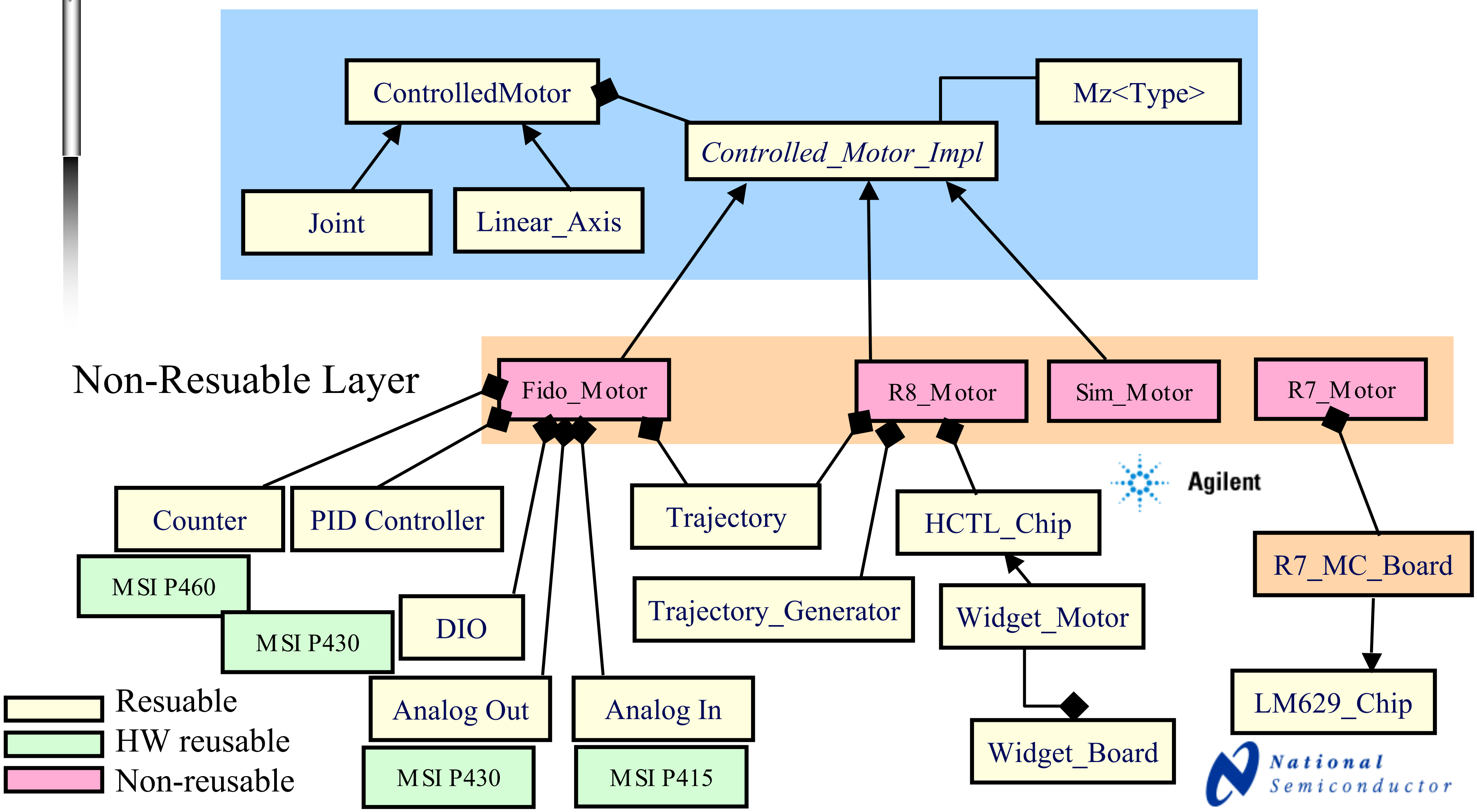
Connecting Bodies and Joints



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

Examples of CLARAty Reusability



Supported Platforms

Rocky 8

VxWorks x86

JPL

K9

Linux

x86

Ames

Rocky 7

VxWorks ppc

JPL

FIDO

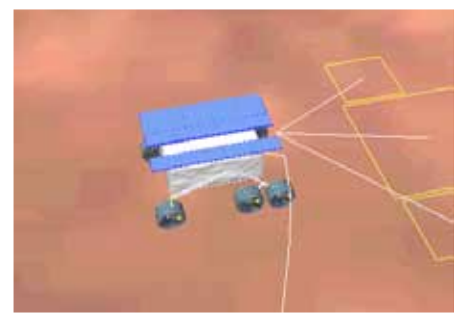
VxWorks x86

JPL

ATRV

Linux x86

CMU

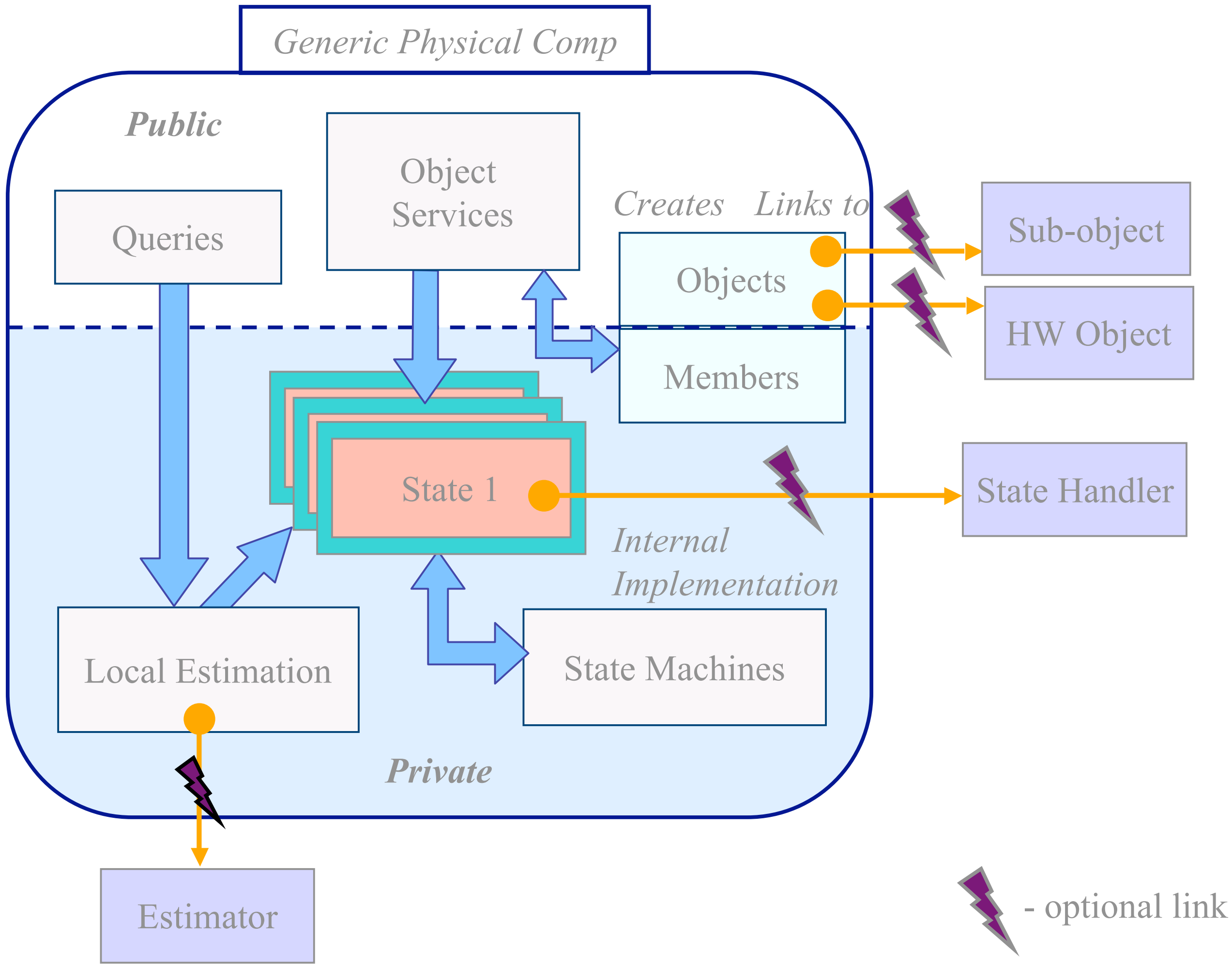


ROAMS

Solaris Linux

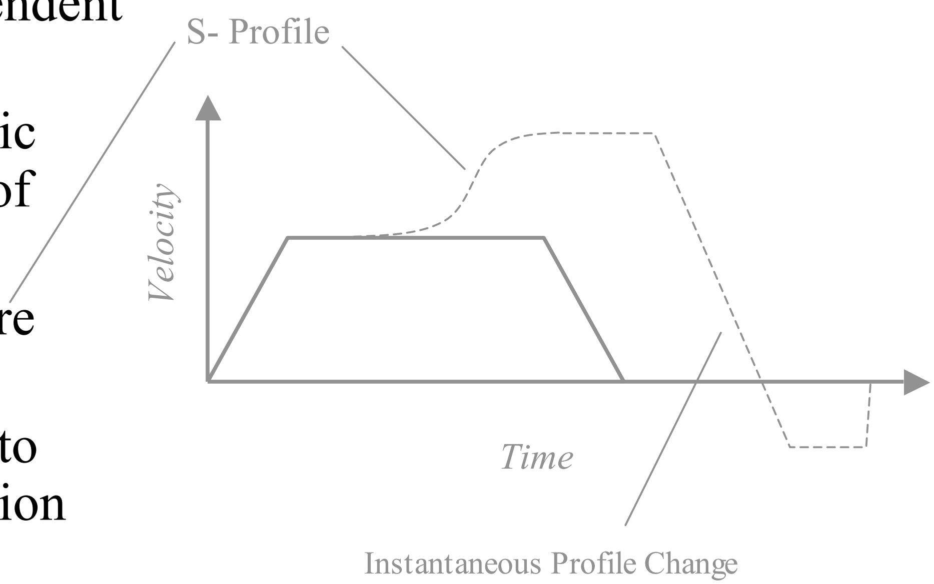
JPL

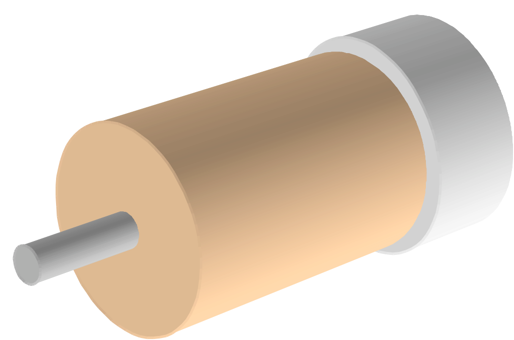
Component Analysis



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

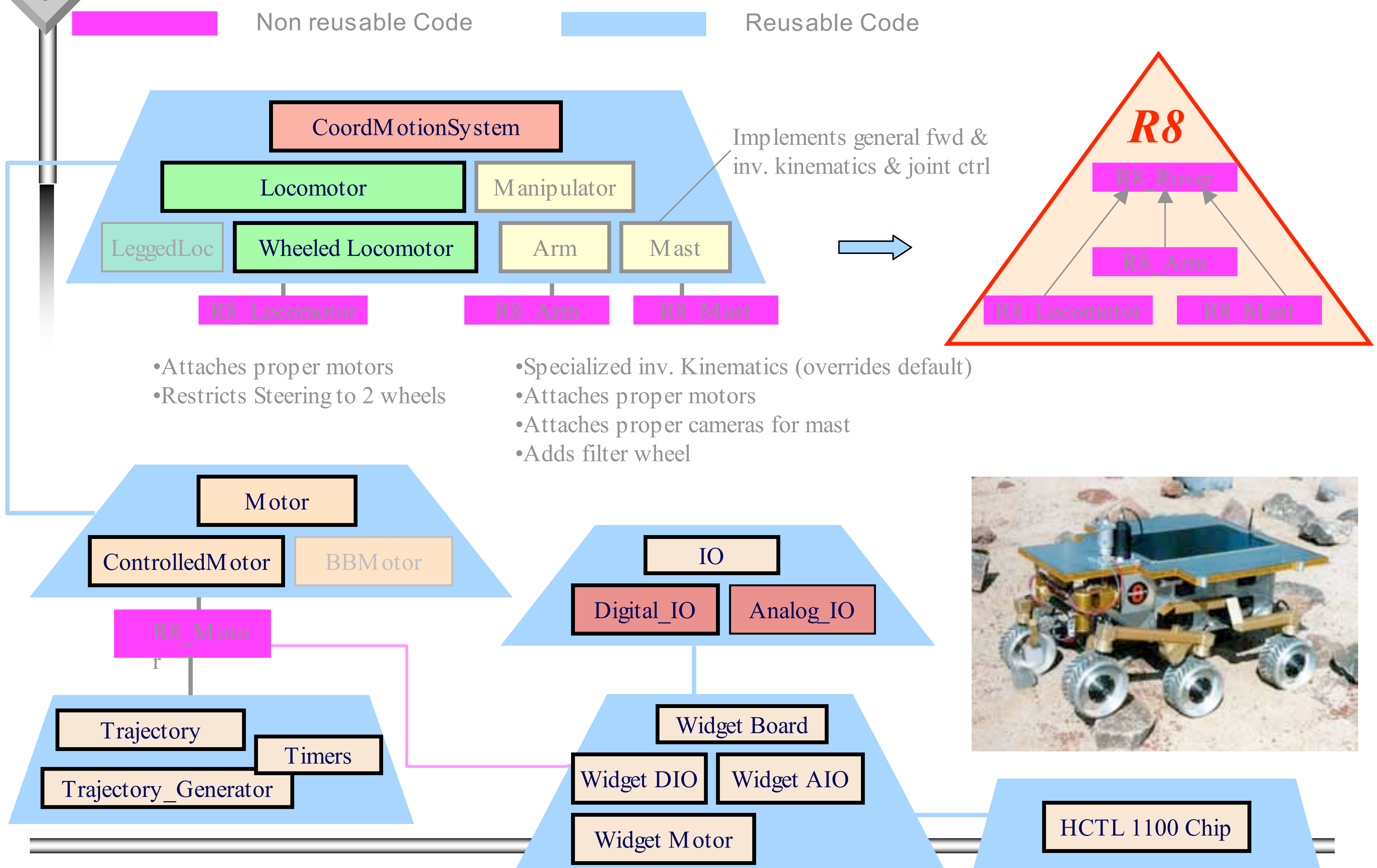
Add

Version 4.0

- Use device and telemetry infrastructure
  Add adaptation to K9

Future
ARC - 2003

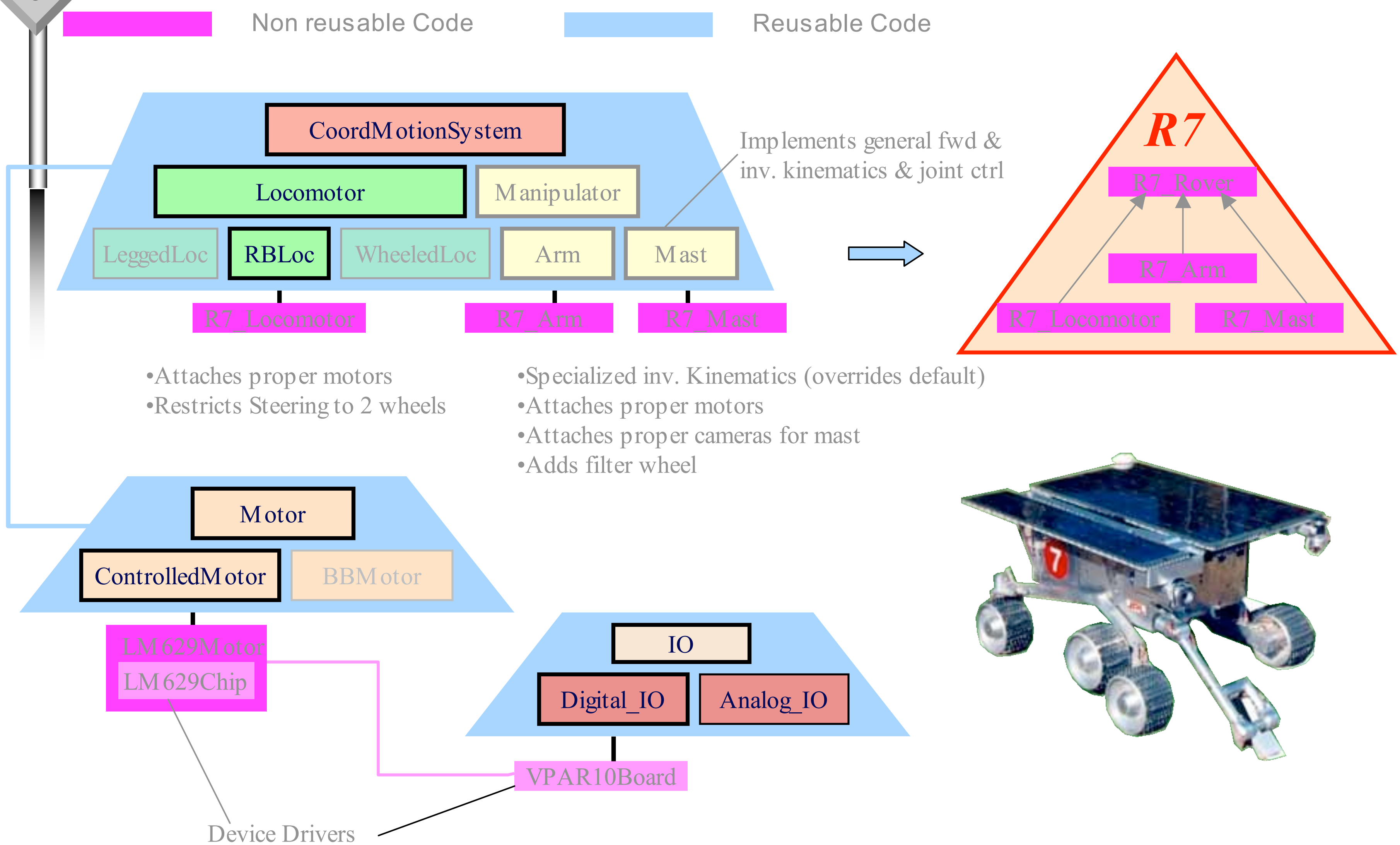
R8 Specific Rover Implementation



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



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