Rover Technology Development and Mission Infusion Beyond MER

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Abstract—This paper describes recent efforts of the Mars Technology Program (MTP) to develop, integrate, and validate new rover technologies for upcoming missions. Missions planned after the current Mars Exploration Rovers require increased autonomy in several usage scenarios: long traverse, instrument placement, sampling, and onboard science data processing. To ensure improvements over current systems, MTP is funding component technology development toward these ends, as well as integration efforts that unify the components to address the larger scenarios. This unified software is expanding a developing infrastructure of common tools for operations, control, and hardware interfacing or system simulation. Using these, validation efforts are underway to quantify the performance of the scenario solutions, and document these for subsequent presentation to the upcoming flight projects.

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1. INTRODUCTION

At the same time the 2003 Mars Exploration Rovers (MER) were being constructed and sent to Mars, there has been a significant effort to move beyond their robotic capabilities for future rover missions. The primary efforts have centered around a large rover mission for 2009, named Mars Science Laboratory (MSL). More recently, plans for two other follow-on rover mission have also been taking form: Mars Sample Return (MSR), and Astrobiology Field Laboratory (AFL). Each of these missions has different objectives, but there is significant overlap in the operational scenarios and underlying technologies required for success. The Mars Technology Program has been funding competitively selected research, and mission focused integration with validation, to mature these technologies for use by the upcoming missions.

Each of the MER rovers were designed to operate for at least 90 days, while traversing at least 600m away from their landing sites near the Martian equator. The rovers are approximately 1m in length, 185 kg, and solar powered. They carry remote imaging sensors on a mast, as well as contact instruments on an arm. Typical operations include driving days, and instrument placement days. Driving days include navigation as far as 100 vehicle lengths, to locations specified in panoramic imagery. Instrument placement operations require three day approaches to rocks of interest, with subsequent contact with and measurement of the target.

MSL is currently planned to be a much larger rover than MER, and designed to last at least one Martian year (668 Martian days, each of which are 40 minutes longer than an Earth day). It would traverse at least 20 km in this time, and would be capable of visiting high latitudes where it may need to operate in colder temperatures and in reduced illumination (including night). As illustrated in Figure 1, its design is similar in shape to MER, but double its proportions. The payload includes a drilling system to get rock samples for onboard processing.

MSR is in the very early stages of planning, and currently envisioned to be a combination lander and rover to be launched in 2013. Each would have the capability to gather rock and soil samples, providing redundancy for the sample

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[2] IEEEAC paper #1641, updated January 23, 2005

acquisition. Since the ascent vehicle has a limited surface life, all sampling operations must be carried out in a shorter period of time than the previously described missions. Therefore, rover autonomy should be greater to increase productivity and efficiency. Also, due to the split of resources between rover and lander, the rover must be smaller than MSL without sacrifice sampling capability.

AFL is the least well defined of these missions, possibly launching in 2013 or 2017. It is likely to be designed as a big facility rover such as MSL. But since the signs of extant or extinct life on Mars are sure to be very scarce and subtle, the system may need to be substantially more intelligent than its predecessors.

Given these missions as objectives, current MTP rover research is dedicated to enabling and enhancing the planned capabilities. The next section, describes the use-case scenarios which research should address. Section 3, describes some specific technologies developed by MTP and employed in the MER mission which might be leveraged for future missions. MER infusion was largely a result of technologist joining the project, underscoring the need for a subsequently developed process employed by MTP and described in Section 4. Governed by this new process, there have been two cycles of competitively selected research described in Section 5. These technology products are then integrated in a structured way as described in Section 6. Section 7 describes how the integrated technologies are being validated against the specified use-cases. Finally, Section 8 describes a new software system scheduled for near-term release to aid this overall infusion process.

2. ROVER MISSION SCENARIOS

There are two primary mission capabilities designated by MSL: Long Traverse, and Approach & Instrument Placement (A&IP). In addition, research is also addressing the enhancing capability of autonomous science data processing.

Long Traverse requires autonomously driving distances on the order of 100 times the vehicle length. Many terrain features of significance, such as obstacles, will typically not be apparent in panoramic imagery provided to operators by the rover from its starting location. High resolution imagery from orbit may help map large scale terrain qualities, and may be used by operators or onboard the rover for global path planning. However, determining the original position of the rover and maintaining an accurate estimate during the traverse become important issues. This is especially true in soft terrains which cause slippage, or featureless terrains where visual correlation is difficult.

A&IP requires approaching a terrain feature designated by scientists from up to 10 vehicle lengths distant, and reliably

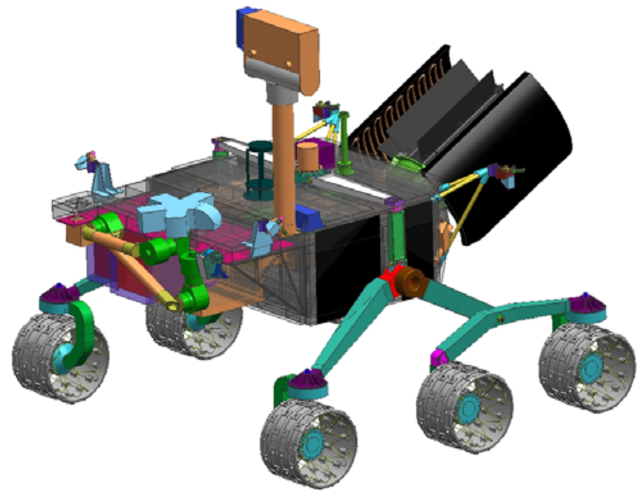

Figure 1 – Pre-decisional concept drawing of the 2009 MSL rover. For scale, the length is 2m.

placing an instrument on the feature. An important facet of this capability is keeping track of the target even while traversing toward it through rough terrain. A continuous line of sight may not possible, and differences in lighting or view angle may complicate the process. Also, the rough terrain expected for rock fields of interest can make navigation and position estimation difficult. As the desired target becomes close to the vehicle, another complication may be introduced by the necessity to use cameras with different focal length, stereo separation, field of view, and vehicle mount position. Finally, once the target is within the workspace of the manipulator with science instruments, the arm must be deployed safely and reliably to the target location. This last operation may require repetition for surface preparation steps, require force control for grinding operations or surface compliance, and must handle contingencies through lighting changes and thermal cycles during long deployments.

Finally, autonomous science data processing is seen as a mission enhancing capability that may be valuable during a 500 day missions. Three types of data processing are possible:

Data Compression – This provides passive categorization, or compression of data collected for other purposes. Examples might be as simple as cropping sky from images taken for geology, or using navigation imagery to quantify rock distributions during traversal.

Activity Suspension – This requires detection of known features using periodic measurements, and aborting current plans if specified conditions are met. An example of this type of capability would be to monitor periodic spectral readings and abort the remainder of a traverse if a carbonate signature is detected.

Conditional Activity Initiation – This is similar to above, except rover activities are initiated without further review by ground operators. An example would be suspension of a long traverse and initiation of an instrument placement operation, based on data collected during the traverse. While this level of capability is a goal for the technology program, it is currently considered by many as too aggressive for MSL.

3. MER ROVER TECHNOLOGY USAGE

In early 2004, the MER twin rovers arrived on Mars, and have proceeded to operate continuously through the year. During the mission, a number of new capabilities have been utilized to drive to science targets and place instruments against them. The robotic capabilities are the product of previous NASA funding in the research program, including:

a. Stereo vision

Each MER rover has three pairs of cameras available for **onboard left/right image correlation** resulting in depth perception and terrain elevation models. These are used primarily for autonomous navigation of the vehicle, but also for manipulation and instrument placement [1,2].

b. Obstacle Detection and Navigation

To avoid obstacles and navigate to the goal, MER uses a software package called **GESTALT** [2], which estimates the local terrain traversability, and steers the rover to avoid nearby sensed obstacles while trying to get to the specified goal.

c. Vehicle Kinematics

Kinematic computations are used to determine both steering angles and wheel rotations needed to effect the desired movement of the vehicle. The inverse is utilized to estimate actual motion of the center of the vehicle based on individual wheel motions. Similar mapping between joint angles and end effector motion is computed for the arm on each rover. Knowledge of the rover model and the kinematics enables onboard **arm collision avoidance** [3] with the rover structure.

d. Position Estimation

In addition to position estimation of the vehicle based solely on the wheel motion, inertial sensors, and imagery are used. Integration of **angular rate** sensors provides an estimate of heading, which is much better than that obtained from wheel measurements. Feature tracking in stereo imagery from the body and mast cameras enables the computation of "**visual odometry**" [4]. **Sun sensing** is used at the end of the day to obtain an independent measurement of the vehicle orientation, both for navigation planning and communications antenna pointing. Also, overlapping panoramic images are used to reregister the rover position after several traverses, using a technique of "**bundle adjustment**" of extracted feature points [5].

e. Science Activity Planner

SAP is used for collaboratively selecting science targets and establishing science activity sequences within mission resource constraints [6]. It may be used for **distributed operations** by scientists located away from the JPL mission center. A version of the software called **Maestro** has also been released for public relations purposes.

f. ROAMS Simulation

A subset of the ROAMS rover simulation environment is being used in MER for previewing rover commanded actions, and post-viewing telemetry [7].

4. ROVER TECHNOLOGY INFUSION

As more surface missions are anticipated for Mars, with elevated expectations of mobility and autonomy, it becomes important to develop a process for capture of advanced research capabilities in flight systems. Up to the present, this has often been accomplished by having technology developers assume positions on the flight team, and bring their technology components with them. However, such a process is not always feasible or desirable, and is biased against technology developers not located at the institution of the flight project.

The Mars Technology Program has attempted to remedy this situation by developing a process by which technology providers infuse their component technologies into a coherent whole, where they may be leveraged by other participants, compared with competing techniques, and validated for capture by upcoming missions. This process is designed to be distinctly different than its predecessors in the way it organizes participants, captures their technology products, and experimentally validates the resulting system capabilities prior to infusion into the mission. A diagram of the process flow is shown in Figure 2, and described below

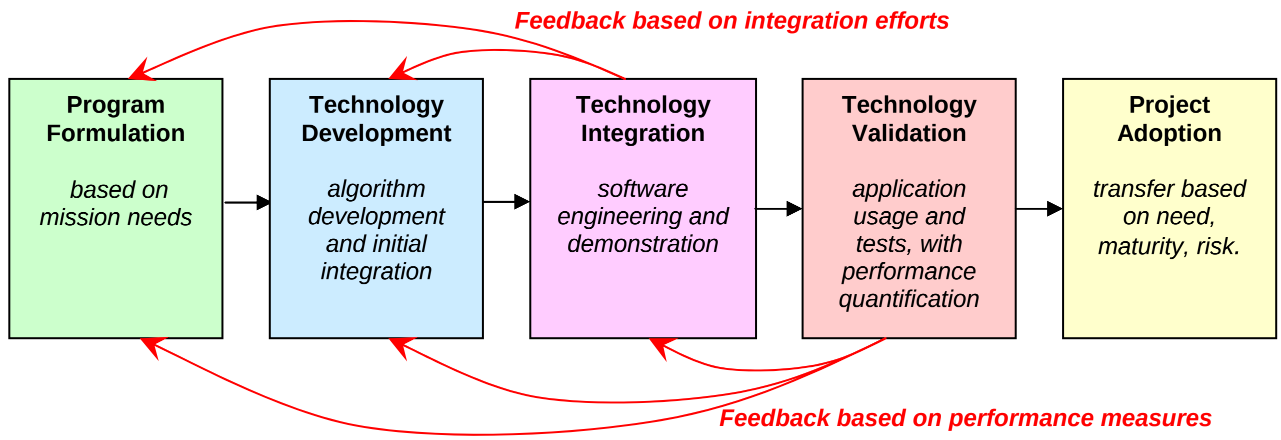

Figure 2 – Rover Technology Flow

First, during the **Program Formulation** phase, the areas of needed technology are determined by MTP working with the current and upcoming missions. Consideration is given to both enabling and enhancing technology, as well as the period of time before mission capabilities must be solidly defined, mostly disallowing further technology infusion. Based on this analysis, calls for proposals are released, typically through the NRA process, and technology providers are competitively selected [8]. Resultant proposals must demonstrate that the technology to be provided is reasonably mature, addresses mission needs, lives within mission constraints, and can be transferred to MTP within the period of funding. Maturity should be at Technology Readiness Level (TRL) four at the start of funding, and demonstrated in the integrated MTP system at level six by the conclusion of funding [9].

Second, during the **Technology Development** phase, subsystems and algorithms are refined and demonstrated, and subjected to initial integration. Especially in the case of algorithm development, the product of the effort is not just journal papers and documented results. Rather, the primary product of most providers is software delivered to MTP by integration into a common software environment. Additionally, the technology providers are required to submit a Functional Design Document (FDD), and other supporting information (e.g. data sets) that facilitate integration. These delivery requirements are also used for technology not directly funded by MTP but of value to it – this has include technology products from other NASA and DoD programs, as well as legacy technology developed in years past under funding from other sources.

Third, during the **Technology Integration** phase, algorithms are integrated into a common system, *the Coupled Layer Architecture for Robotic Autonomy*, or CLARAty [10]. This software infrastructure is being actively developed and provided by MTP, and its support team assists technology providers with integration of their software products. Further, the CLARAty infrastructure itself is being developed through a multi-institutional collaboration between JPL, NASA Ames Research Center (ARC), Carnegie Mellon University (CMU), and the University of Minnesota (UMinn). CLARAty will be reviewed more in Section 6.

During the Integration process, deficiencies and gaps may be discovered in the technology itself, or in its relation to other components. Problems with the software or documentation deliveries from the technology provider are reported back to the team for immediate correction, or to guide their future work. In cases where resolution of the problems are outside of the defined scope of funding to the development or integration teams, feedback is provided to MTP for its future planning purposes. In some cases, program reserves are employed to address the problem, or future proposal calls are targeted accordingly.

Fourth, after integration is complete, **Technology Validation** may be preformed within the context of the mission scenarios described in Section 2. Validation consists of analysis, simulation, and experimentation designed to evaluate the performance of the software and algorithm over its advertised envelope of operation. Typically this requires tests of individual components, as well as related components working together. Also, since CLARAty provides abstraction of, and support for numerous test platforms, the performance may be elucidated independent of single platform particularities. Included amongst the platforms is a rover simulation system, ROAMS [7], which allows for test trial repetition not possible by slower experimentation with physical rovers. Also, the experimentation helps to validate the simulation fidelity.

As a result of, or during the validation process, problems may be revealed in either the algorithms, their software representation, or their integration into a common software

Research Topic	Lead	Organization	Component Technologies
Driving on Slopes	Matthies	JPL / Caltech	visual odometry, slip compensation,
Visual Tracking	Nesnas	JPL / Caltech	2D / 3D visual rock target tracking
Autonomous Science	Roush	NASA Ames	onboard spectral match, rock/feature finding
Health Diagnosis	Dearden	NASA Ames	particle filter based detection & diagnosis
Traverse Planning	Stentz	CMU	path and resource usage planning
Mapping	Olson	Univ. of Washington	wide baseline stereo, elevation map seaming
Terrain Estimation	Iagnemma	MIT	sinkage/slippage & terrain property estimation
Position Estimation	Borenstein	Univ. of Michigan	fuzzy logic position estimation

Table 1 – MTP funded Technology Development, 2001-2004

system. These problems are documented and reported back to the technology provider and integration teams for correction. Also, since the validation typically combines multiple technology components and stresses them in numerous scenario variations, deficiencies can be revealed which are not readily addressed by developers or integrators.

These problems are reported back to the program for its consideration. In some cases, the validation team has been directed to develop patches. In other cases, existing technology components have been sought from other sources to bridge gaps. In at least one case, an MTP developed technology was revealed to be deficient and a new iteration of technology develop for this algorithm was started.

When validated technologies perform satisfactorily within most use cases, the results are presented to the mission customer, so that the software might be considered for **Project Adoption**. This does not guarantee that the flight project will use the software as is – such decisions are made by the software team on the project. However, since mission infusion will come from a single, validated source of software, the number of team interfaces and complexity of the process is drastically reduced. Also, since the technology products have been decoupled from the individual providers, there is no implicit need to bring the developers into the mission to ensure success. This last point is especially important since the extended community of technology providers assumed by the initial competitive selection is distributed throughout the nation, and not readily available for mission support roles. But their technology components can and will greatly enhance the mission performance.

This model assumes the willingness of the project to consider the adoption of third party software if it is shown to be of sufficient maturity through the validation process. As evidence of this openness, it is important to note that open-source third party software was used by MER in limited ways for both operations and flight software. To date it has not been used onboard for controls, although informal polling of mission engineers has raised no objection to this case. Therefore, this MTP process is designed to take advantage of the demonstrated pathway for open-source code usage, and exercise is it for infusion of integrated and validated software emerging from competitively selected research. But even in the case where research software products are not directly used by a flight project, they will serve as a valuable starting point for further development by the project software team, providing great savings and demonstration of improved functionality.

5. MTP ROVER TECHNOLOGY

The Mars Technology Program has recently started its second cycle of Technology Development under the process described in Section 4. The technologies developed in the first cycle were previously described [11], and are summarized in Table 1.

In 2004, a set of new research tasks were selected through the NASA Research Announcement (NRA) process [8]. Those new efforts which will provide algorithm and software improvements for rovers are summarized below:

a. Rover Navigation for Very Rough Terrain, CMU

This research will build on previous research which resulted in the *Morphin* local navigation algorithm [12]. Extensions will be explored for configuration space motions in the immediate vicinity of the vehicle based on simulation analysis of dense terrain maps obtained with stereo vision.

b. Very Rough Terrain Motion Planning For Rovers, CMU

This work will investigate techniques for fusing efficient nonholonomic trajectory generation with local and global path planning techniques [13].

c. Reliable and Efficient Long Range Navigation, CMU

Follwing a prior effort also funded by MTP, this research will continue to address planning for long traverses under terrain, power, lighting, and communication constraints [14].

d. Multi-Sensor Terrain Classification & Navigation, MIT

Combining and extending MIT & JPL research from the first round competition, this effort will use correlated vision and contact information to estimate terrain properties, and use them to plan driving routes for best traction [15].

e. Long-range Autonomous Rover Localization, Ohio State

This research will extend mapping technology partially funded previously by MTP, and matured for ground operations during the MER mission. Techniques for bundle adjustment of range maps from panoramic, traverse, and descent imagery, provide accurate maps and localization [5].

f. Single Command Approach & Instrument Placement, JPL

This work will leverage prior research funded by MTP under the FIDO rover field trials of last decade [16], as well as recent developments at NASA Ames [17], to provide improvements in tracking, localization, and manipulation algorithms.

g. Whole Rover-Arm Coordination, Stanford

This effort will explore the use of reduced degrees-of-freedom manipulators on mobile rover platforms performing tasks relevant to Mars exploration [18].

h. Universal Decision-Layer Executive, NASA Ames

Unlike the above research in rover functionality, this work will develop a new executive for the CLARAty Decision Layer, uniting for the first time other executives developed in and out of NASA [19,20,21].

6. MTP ROVER TECH INTEGRATION

There are three complementary aspects to rover onboard control algorithms integration in MTP: enabling the exchange of competitive components, structuring the categorization of complementary components, and providing the hierarchical grouping of these for subsystem abstraction. Each aspect is addressed by ongoing software engineering efforts of the CLARAty integration team.

Competitive Components

System components that have duplicate functionality (but not performance) come into existence naturally through both the evolution of existing techniques, as well as the nature of the funding process. In some cases, down-selection of supported algorithms is reasonable to reduce system complexity when clearly superior alternatives emerge. In other cases, similar algorithms may coexist as alternatives suited to varying circumstances of operation. Two areas where a notable number of alternatives have emerged are local navigation and position estimation. Greater complexity has led to better performance in some cases, but a thorough investigation of the trades between complexity and performance has not yet been completed, since integration is still underway. For this reason, it is important that the integration effort provides common interfaces to competitive algorithms, so that they might be exchanged for one another in the final system, allowing head to head comparison of performance. As an example, Table 2 shows a set of legacy and newer position estimation algorithms that have been recently integrated into a common CLARAty software structure, as a preamble to formal performance evaluation.

Name	Year	Sensor Inputs	Algorithm type
Simple	----	wheel odometry	Forward kinematics
Sojourner	1997	wheel odometry z-axis gyro	Bias averaging, signal integration
Rocky 7	1998	wheel odometry sun sensor tilt sensors	Incremental path summation
FIDO	1999	wheel odometry z-axis gyro	Extended Kalman Filter
Visual Odometry	2004	stereo imagery	Feature tracking
6DOF EKF v1.0	2004	3 gyros 3 accels	Extended Kalman Filter

Table 2 – Position Estimation available in CLARAty

Complementary Components

As competitive algorithms are grouped, multiple categories of components emerge. In addition to position estimation and local navigation mentioned above, other categories include arm control, visual tracking, obstacle detection, etc. Once implemented in software, these categories form *classes*, with well defined application program interfaces (APIs). In CLARAty, similar classes have been grouped into *packages* for leveraging of common software infrastructure. The list of current packages is shown in Table 3, providing a sense of scope of the software infrastructure. (Note, not all packages are of equal size or maturity.)

To make a working system, complementary software from different classes is combined to provide an ensemble of system functionality. The structure is designed to eliminate gaps or overlaps that might exist with such mixing and matching of components. In addition, CLARAty allows such ensembles of functionality to be hierarchical, as described next.

Hierarchical Components

The CLARAty Functional Layer is designed to be hierarchical, providing interfaces and encapsulated

Functional Layer	Decision Layer	Rover Adaptations
Sensors	Execution	Rocky 8
Motion Control	Planning	FIDO
Locomotion		K9
Manipulation		Rocky 7
Vision		ATRV Jr
Estimation		ROAMS Simulation
Communication		
Navigation		
Path Planning		
Behaviors		
Math & Transforms		
Base		

Table 3 – CLARAty Software Packages

capability at different granularities. This has two benefits for integration.

First, previously captured technology can be combined and referenced as a whole. An example is the creation of a rover class that abstracts motor control, wheel coordination, position estimation, and other functionality. This also allows for a stable API at the rover class level, even if there are changes in the constituents, such as exchange of competitive components, or extensions of the APIs.

Second, and probably more important to technology integration, a hierarchical structure allows for wrapping of new technologies that are not expressed in native CLARAty software. Wrapped technology is valuable for several reasons:

- It provides a first step of integration, allowing exercise of the delivered technology without disturbing it.
- It provides an interface to legacy versions of technology, even after subsequent versions are refactored to leverage the standard CLARAty system classes.
- It provides an interface to third party software libraries.
- It allows for a common interface to subsystems that are implemented in hardware on some platforms and software on others.

7. MTP Rover Tech Validation

Validation of software technologies introduced in Section 5, is centered on usage scenarios described in Section 2, and leverages the software structure described in Section 6. To date, four formal validation reports have been completed: JPL stereo vision, 2D visual tracking, FIDO EKF position estimation, and visual odometry. Two others are in progress: 2D/3D visual tracking, and GESTALT local navigation.

Validation centered on Approach & Instrument Placement (A&IP) provides a good illustration of use of the component structure described in the previous section. To accomplish A&IP in one command cycle a number of technologies from different sources must be combined. While the quantified performance of the composite system is ultimately the product desired by the flight project customer, an understanding of this performance and its envelope is best achieved by systematic measurement of the subsystems. In some cases, multiple competitive sub- systems must be evaluated to find satisfactory performance.

Figure 3 shows the approach portion of A&IP. After a target has been selected by users, the rover must navigate through the environment while keeping track of the target. Implicit also is the need to maintain an accurate estimate of the rover position and point or switch cameras used for tracking. To validate this system, each component must be validated separately, and then the ensemble tested together. Since navigation and pose estimation is shared with Long Traverse Validation, some performance results have been imported from this other effort. Similarly, stereo vision performance was determined by A&IP and exported.
For some steps in Target Approach, multiple algorithms are being validated to find sufficient performance. An example is camera handoff, where two algorithms from JPL and Ohio State University have been tested, and a third from NASA Ames is planned for evaluation.

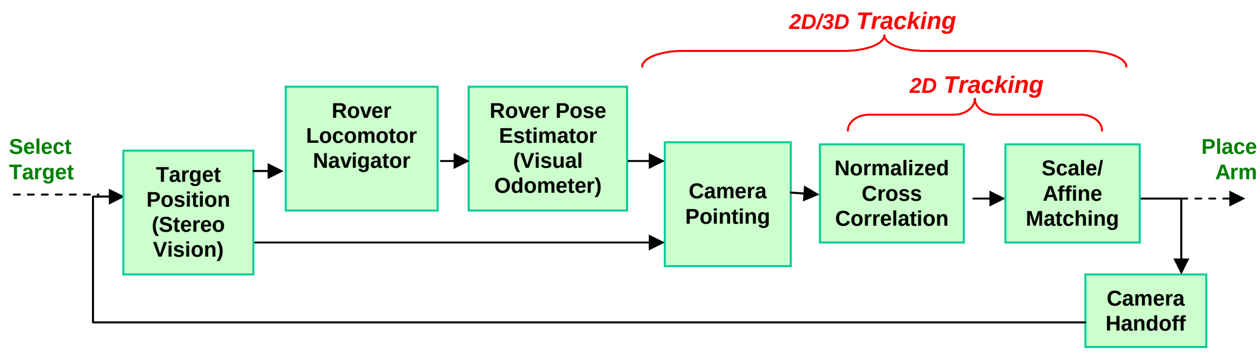

Figure 3 – Visual Tracking Components for Approach & Instrument Placement Validation

Even when multiple algorithms are not explicitly evaluated, the software structure allows for substitution in the future if desired. For example target-positioning stereo vision has been provided by JPL, but the CLARAty interface allows for the use of SRI or NASA Ames stereo vision. Due to Intellectual Property and flight software restrictions, JPL stereo is not planned for release outside of the institution. Similarly, SRI stereo source code is not readily available, (but its use is an example of code inclusion through wrapping). Therefore, open source release of NASA Ames stereo vision is currently planned, making future validation of its performance desirable.

The validation process makes evaluation of alternate algorithms much easier than the initial first validation. Calibrated data sets and test scripts are stored, along with algorithm results. These can be used both to test alternate algorithms, as well as for regression tests on previously validated software.

Finally, it is important to note that the ensemble illustrated in Figure 3 is accessed through a *tracking class* that hides these details. Future changes in the constituent algorithms, or the data flow illustrated, is hidden by the tracking API so that other software is isolated from these changes. While it is possible that modifications could change behavior in ways that disturb other subsystems, the encapsulating API is a first level of defense. Also, typically changes are made to improve performance, therefore making it less likely to cause detrimental effects outside of the tracking subsystem.

8. ROVERWARE

As a further step toward system integration, and to provide a common development and test environment to MTP participants, we have also be developing an end-to-end rover software system called *Roverware*. This product is an integrated version of CLARAty, with the Maestro operations interface [6], and the ROAMS rover simulator [7].

Figure 4 shows a block diagram of the Roverware system. On the left is the operations interface software, Maestro. It displays telemetry, particularly imagery, and enables the creation of command sequences to be issued to CLARAty. The blue and pink boxes to the right of Maestro are the CLARAty Functional and Decision layers. The Functional Layer provides all onboard control of the rover system, while the Decision Layer optionally provides onboard planning, scheduling, and contingent execution. The ability of Maestro to upload plans has been demonstrated, but is not part of the first Roverware release. Also, it is important to understand that a copy of the CLARAty software is available on the ground for use by Maestro before any command sequences are communicated to the rover. Therefore, Maestro may use the same software as the rover for evaluation of everything from arm kinematics to plan prioritization.

CLARAty can interface to either real hardware, shown in gray, or to a simulation of real hardware, provided by ROAMS and shown in green. Real hardware only interfaces to the CLARAty software at its lowest level, through device drivers, but simulation may interface at higher levels of abstraction for computational efficiency.

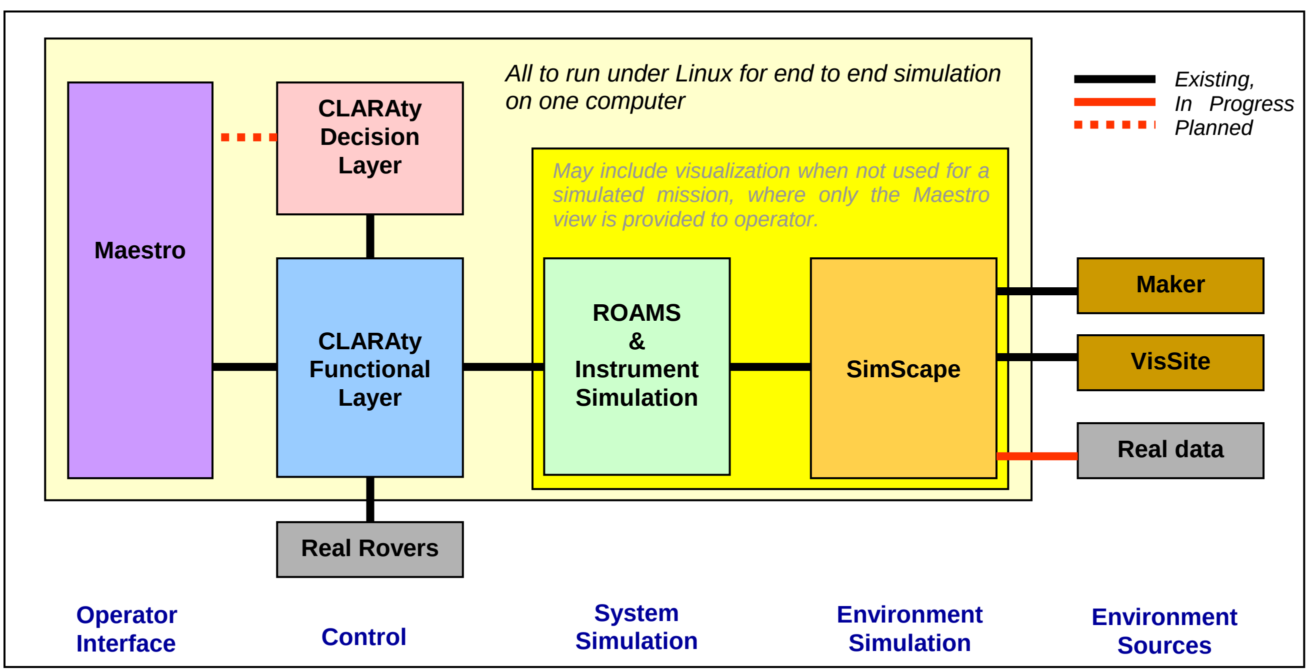

Figure 4 – The Roverware architecture for combining Operations, Control, and System / Environment simulation.

The planned default hardware provided in the first Roverware release will be the ATRV Jr., and a model of this same hardware is also being created for use in the ROAMS simulator. Instrument simulations, if any, are interfaced similarly. Note that all data flow from the real or simulated systems is obtained by CLARAty and communicated to Maestro. Therefore, both hardware and simulation modes use the same control software, and the operations interface is unaware of any changes of the source of data.

Similarly, ROAMS is interfaced to an environmental simulation database called SimScape which obtains its data from a number of sources including terrain synthesis programs (e.g. Maker, VisSite), as well as real data sources (e.g. Mars, terrestrial field tests). Nominal static terrain data will be stored in SimScape and bundled with ROAMS for distribution as part of Roverware. Future modifications to the environmental data are readily possible.

Together, these systems will enable Roverware to provide the user with a simulated or emulated Mars surface mission. They also will provide all of the framework needed to test new usage or algorithmic improvements against a baseline system for exploration. In this way, several objectives for the creation of the Roverware system may be achieved:

- By providing an end-to-end Mars surface mission simulation capability, coupled with transparent migration to field test usage, MTP is soliciting user feedback from the science and engineer community on the efficacy of system and algorithm improvements developed by the program.
- By providing a full suite of capabilities to the Mars rover community, MTP hopes to make researchers more efficient as well as better aligned in practices and tool use.
- By providing the same software to others in the academic community who are not currently receiving MTP funding, the program hopes to motivate students and researchers, generating good will for NASA and possible surface system improvements pro bono.

The first version of Roverware is planned for release by September, 2005. While the software will be engineered for easy installation and use by end users, it will also allow for source code access. Providing source will engender trust by the users, enable compilation on desired platforms, and provide for modifications by the community. However, permissions for source release have been slow to come, due to concerns over ITAR and intellectual property issues. It is believed at this time that all major obstacles have been removed for a timely completion of the Roverware release this year.

9. Summary

This paper has provided an overview of the MTP technology development, integration, and infusion process for the upcoming 2009 MSL mission and beyond. A review of pertinent MER robotics capabilities has been provided, and the need for a new process for technology infusion into future missions has been discussed. This process has been described, and the candidate technologies to enter the process have been reviewed. Aspects of the CLARAty software system that facilitate the technology capture have also been reviewed, along with their use by the software validation efforts. Finally, the new Roverware end-to-end software system has been introduced as a further step toward alignment of development, integration, and testing of new technologies for infusion into future Mars missions.

10. Acknowledgements

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BIOGRAPHY

***Richard Volpe, Ph.D**., is Manager of the Mobility and Robotic Systems Section of the Jet Propulsion Laboratory, California Institute of Technology. The section is a team of over 80 robotics engineers doing research and space-flight implementation of robotic systems for Roving, Ballooning, Drilling, and other modes of in-situ planetary exploration. Key capabilities include vision, sensor processing, advanced controls, man-machine interfaces, simulation, and system design. Richard's research interests include natural terrain mobile robots, real-time sensor-based control, manipulation, robot design, software architecture, and path planning.*

From 2001 through 2004, Richard served as manager Mars Regional Mobility and Subsurface Access in JPL's Space Exploration Technology Program Office. In addition to guiding technology development for future robotic exploration of Mars and the Moon, he has been actively involved in 2003 & 2009 rover mission development. This has included managing internal JPL rover technology development, as well as external university research funded by the Mars Technology Program.

Richard received his M.S. (1986) and Ph.D. (1990) in Applied Physics from Carnegie Mellon University, where he was a US Air Force Laboratory Graduate Fellow. His thesis research concentrated on real-time force and impact control of robotic manipulators. In December 1990, he became a Member of the Technical Staff at the Jet Propulsion Laboratory, California Institute of Technology. Until 1994, he was a member of the Remote Surface Inspection Project, investigating sensor-based control technology for telerobotic inspection of the International Space Station. Starting in 1994, he led the development of Rocky 7, a next generation mobile robot prototype for extended-traverse sampling missions on Mars. In 1997, he received a NASA Exceptional Achievement Award for this work, which led to the design concepts for the 2003 Mars rover mission. In 1999 and 2000 he served as the System Technologist for the Athena-Rover, then part of a 2003 Mars Sample Return Project. Until mid 2001 he was the Principal Investigator for the CLARAty and Long Range Science Rover Research Projects.

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