An earlier report [32] explained how autonomous navigation and control of a mobile robot could be defined as a hierarchical system. That report was based on a survey report [8] that described the current trend toward hierarchical systems for motion planning and control of mobile robots. The following discussion again examines the hierarchy system, with particular regard to the wheeled mobile robot being considered [41] for exploration of Mars. In an effort to ensure the utmost reliability, the upper levels of this hierarchy would regularly plan or revise the detailed paths for the rover to follow. The lower levels of the hierarchy would be responsible for driving the rover along the previously determined paths, through otherwise unexplored terrain. These lower levels are of particular significance to the current project.

A hierarchical navigation and control structure facilitates the tractable combining of sophisticated systems, each operating on a different spacial and temporal scale, into a single cohesive system. Each level of the hierarchy first receives an instruction from the immediately higher level, then performs some form of reasoning or processing based on established knowledge and/or through sensor analysis, and then finally defines a more precise set of sub-goals for the next lower level. One such hierarchy, considered in this work, consists of four levels [33]; the *Planner*, *Navigator*, *Pilot* and *Controller*.

Planner

The planner is primarily concerned with choosing a general route to be followed over a distance of say 100 vehicle body lengths (400m). The planner may receive instructions from humans or through decisions taken by other mission systems. The choice of route would account for the general terrain and vehicle characteristics as well as various mission goals. Factors affecting the planning of the route may include the avoidance of steep hills or large rock formations, a preference for higher ground that would ensure good communications or optimum solar exposure, or the necessity to use the shortest and most efficient route to ensure a specific power safety margin or meet the schedule requirements. This type of planning requires relatively long-range information, which might be supplied by topographical (satellite) maps and possibly long-range (>400m) senors, such as radar. The chosen route is subdivided by the planner into smaller segments, which are individually passed to the navigator for further analysis.

Navigator

The navigator's primary function is to plot a detailed course or path, along each route segment received from the planner, that will be on the order of 10 vehicle bodies in length (40m). The navigation process requires the greatest amount of local "world" sensing, analysis and decision making. The selected path must show great consideration for specific terrain and vehicle characteristics, and the path selection algorithm may be quite similar to that used by the planner. Factors affecting path selection may include hazard avoidance, mobility, stability, power, efficiency, reliability, communications quality and traversal time. Costing functions might be applied to statistically based information, such as grid maps, which indicate probable occupancy or level of hazard. These grid maps are essentially a composite of sufficiently detailed topographic maps and data acquired through a detailed sensor analysis of the immediate area. This analysis would utilize both vision and targetable rangefinding techniques. The physical sensors may include stereo camera, laser and acoustic devices. The sensor analysis must finally result in a symbolic description of the terrain that can be used by a path-selection algorithm.

When the path-selection process has been completed, a simulation of the path traversal may be performed to determine the expected power consumption and stability, and to schedule landmarks or objects to be verified (checkpoints) along the way [3]. If the initial analysis and simulation is acceptable, the navigator must pass appropriate segments of the selected path to the pilot for execution. These path segments should require only limited external sensing, such as that which may be monitored in real-time to control locomotion factors such as position, heading and speed.

It should be noted that the activities of both the planner and navigator are not performed in real-time. That is to say, the rover is stationary during data acquisition and analysis. This state is likely to be required to meet limitations in power and computational speed, however it should also facilitate improved sensing (targeting), external communication and calibration of guidance systems.

Pilot and Controller

The pilot drives the rover along each path segment received from the navigator. Each of these segments, perhaps 1-2 vehicle bodies in length (4-8m), would consist of either position and heading data describing a continuous (relatively unobstructed) path, or specifications for the crossing of a specific obstacle. It is intended that the navigator should have identified and accounted for (avoided) significant obstacles in its definition of a continuous path segment, however this may not always be the case. The pilot should utilize as much real-time "world" and internal sensing as possible during motion. It may stop to signal the navigator when an unexpected hazard is encountered, or it may avoid and later report such a hazard as a matter of course. Deviations from the desired path may result from vehicle-terrain interactions, pilot and controller errors, or through effort by the pilot to avoid close-proximity hazards.

The pilot may have to monitor many vehicle and motion elements in real-time, including position, heading, speed, acceleration, inclination, joint angles, and proximity. Starting from a known position and orientation, the pilot must command the motion of the rover, also in real-time, such that the error between the current and desired path is minimized. This will be accomplished by regularly updating the inputs to the controller. For an increasingly sophisticated controller, these inputs may range in nature from specific wheel torques, speeds and steering angles, to simple definition of the required vehicle velocity (speed and heading). The more sophisticated controller would also have direct access to some of the guidance sensors, further reducing the load on the pilot.

The controller directly operates the wheel motors and steering actuators. The more sophisticated controller, mentioned above, would drive the motors and actuators using the error between the speed and heading received from the pilot and the data received from inertial guidance. The controller may operate the actuators in a speed or force/torque control mode, and would be responsible for maintaining traction (avoiding wheel slip). The actual vehicle trajectory (position and heading) would also be monitored by the pilot. Substantial deviation from the desired trajectory is certainly possible, given the loose sand and scattered rocks of the Martian surface. The pilot may possess information regarding local hazards, possibly through proximity sensing or execution of a potential field algorithm [43], and so may be able to monitor the rover's proximity to such hazards in real-time. Significant normal or hazardous deviation from the planned path segment may require the pilot to make substantial changes to the controller inputs. The pilot may also instruct a change in the control mode (ie. torque or speed) or may direct the controller to actuate the wheels and joints in a specific hazard-recovery or obstacle-crossing routine.

In this navigation hierarchy, the planner and navigator represent functional blocks that are not directly involved with the motion of the rover. The collective actions of these two upper levels is often referred to as navigating, path planning, or perhaps more clearly, *motion planning*. The nature of the real-time interaction, and the relationship between the controller sophistication and the pilot work load, tends to obscure the separation between the functions of the pilot and controller within the navigation hierarchy. The collective actions of these two lower levels is also often referred to as navigating, or alternatively, piloting, trajectory control, or perhaps again more clearly, *motion control*.

Table 1 summarizes the above navigation hierarchy. It should be noted that the same physical sensor or analysis data may be shared by different levels of the hierarchy. Each sensor is listed under a level according to the function of that level and consideration of the spacial or temporal constraints of the sensor or its analysis.

Table 1: Navigation Hierarchy for an Autonomous Martian Rover

	Motion Planning		Motion Control	
	PLANNER	NAVIGATOR	PILOT	CONTROLLER
Perception Range	100 body lengths (400m)	10 body lengths (40m)	1-2 body lengths (4-8m)	internal / tactile
Functions & Operations	- mission interface - plan basic route	- detailed survey - plan safe path - (simulation)	- drive rover - hazard avoidance - obstacle crossing	- motor control - steering control - inverse kin/dyn
Factors & Parameters Considered	- mission goals - general terrain - vehicle mobility - communications - power supply	- terrain detail - vehicle mobility - hazards - efficiency	- path error - hazard proximity - stability - obstacle specs.	- heading error - wheel traction
Resources & Sensors	- satellite maps - radar	- satellite maps - stereo camera - laser scanner - acoustic ranger	- accelerometers - inertial compass - acoustic ranger - infrared edge det.	- accelerometers - inertial compass - steer angle - wheel torque
Computation Load	medium / high (off-line)	high (off-line)	low / medium (real-time)	low (real-time)

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