

Behavior-Based Control Systems for Planetary Autonomous Robot Outposts

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Abstract— Current NASA studies are examining opportunities for the deployment of robot colonies or outposts on planetary surfaces within the solar system in the first few decades of the 21st century. This paper presents the results of some ongoing work in the Planetary Robotics Laboratory at JPL in the area of behavior-based control for cooperative multi-robot systems for a planetary robot outpost. We have recently developed a behavior-based system called BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control) that uses a free flow hierarchy for its action selection mechanism. We report the results of numerous simulation studies of complicated multiple rover missions.

Key words: robot outpost, behavior-based control, multi-robot systems

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1. INTRODUCTION

Robot outposts represent the next stage of exploration for NASA planetary surface studies beyond the Mars Sample Return missions of 2003/2005. Outpost operations include such tasks as the deployment and servicing of power systems and in-situ resource utilization (ISRU) generators, establishing long-life robotic science stations for measurement and communications, construction of beacons and roadways, and the site preparation and deployment of human habitat modules. These outposts must

be more or less self-sustaining due to the high cost of resupply. Robot autonomy within the context of a remote outpost will be constrained by mission mass restrictions, and the harsh nature of planetary surfaces. Among these constraints are relatively low computing capabilities and onboard memory due to power constraints, operation within wide temperature extremes, and navigation over multiple terrain types from featureless flat plains to sheer cliffs. In addition, the complexity of the tasks undertaken by robots making up an outpost push the limits of current control capabilities. A discussion of the needed capabilities for robotic systems for outposts can be found in the study done by Huntsberger, Rodriguez and Schenker [13].

Control architectures for robotic systems can be broadly characterized as planning or deliberative, behavior-based or reactive, and hybrid blends of the methods [19]. The planning systems usually have a high computational overhead and require an environment that is relatively static. A representative system is that of Kosaka and Kak [14]. Reactive control systems, on the other hand, are based on a mapping between sensor inputs and actuators, and as such, tend to sacrifice optimality and goal convergence guarantees for more or less real-time response. Such systems were introduced by Brooks [4] and further extended by Arkin [1], Parker [18], and Mataric [17] among others. The Autonomous Robot Architecture (AuRA) [1], Atlantis [5], and the Planner-Reactor Architecture [16] are some examples of hybrid control systems.

Recently, reactive control systems have gained popularity for controlling mobile robotic platforms on planetary surfaces. This was demonstrated to some extent by the Mars Sojourner mission in the summer of 1997. Two laboratory prototype rover systems for planetary surface missions include the Sample Return Rover (SRR) and the Field Integrated Design and Operations (FIDO) rover, both shown in Figure 1, which are currently being field tested at the Jet Propulsion Laboratory in Pasadena, CA, USA. These rovers are among a wide class of planetary surface rovers developed at JPL which include the Long Range Science Rover Rocky 7. SRR is built for low mass, high speed and mobility, while FIDO includes a full science suite

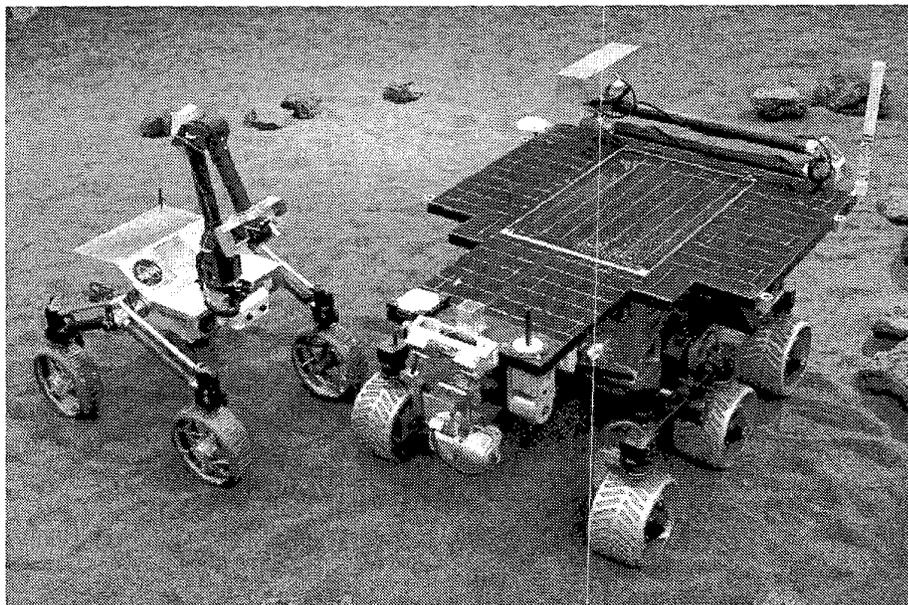


Figure 1 SRR and FIDO rover prototypes in the Planetary Robotics Lab at the Jet Propulsion Laboratory in Pasadena, CA, USA.

equivalent to the 2003 Athena system. These rovers use a traditional finite state control system for navigation and goal achievement. Such a reactive approach doesn't scale well when multiple rovers are cooperating on a task, due to the large number of potential states that can occur.

Behavior-based systems approach autonomy from the standpoint of collections of behaviors. These run the gamut from the purely subsumptive, reactive single robots detailed by Brooks [4] to cooperative multiple robot systems [2, 3]. The wide range of possible behaviors that are needed for a planetary rover obviates the need for an action selection mechanism (ASM) to provide the correct behavior for any given situation. Comprehensive reviews of behavior coordination (or action selection) mechanisms can be found in Arkin [3] and Pirjanian [19]. Recent work of Pirjanian and Mataric [19, 20, 21] using Multiple Objective Decision Making (MODM) provides formal tools for generating strategies that can guarantee an appropriate trade-off between the optimal solutions, which are possibly not reachable in a planetary surface environment, and *Pareto-optimal* or *Satisficing* solutions.

BISMARC (**B**Biologically **I**nspired **S**ystem for **M**ap-based **A**utonomous **R**over **C**ontrol) is a hybrid wavelet/neural network based system under development at JPL [12]. The BISMARC architecture is shown in Figure 2. Previous simulations demonstrated that the system is capable of control for multiple rovers for multiple cache recovery [6] or manned habitat site preparation [11]. Another study extended BISMARC to include fault tolerance in the

sensing and mechanical rover subsystems [7]. The vision subsystem in the original BISMARC implementation relied on the generalization capabilities of a fuzzy self-organizing feature map (FSOFM) neural network [8]. A better vision subsystem based on camera models combined with tilt sensors that is fully integrated into the BISMARC framework was recently developed [9]. A comprehensive review of neural network systems for rover navigation and control can be found in Huntsberger and Rose [12]. The next section gives a general overview of BISMARC, followed by some experimental studies and a concluding section.

2. BISMARC OVERVIEW

The original BISMARC system had three levels and used a hybrid mix of neural networks and behavior-based approaches [12]. The first level performed a wavelet transform on the rover's stereo image pair, the second level input these processed images into an action generation navigation network, which fed into a third level action selection mechanism (ASM) network modeled after the DAMN architecture of Rosenblatt and Payton [22]. The first and second levels of BISMARC have been replaced with the DriveMaps path selection system currently used on SRR and FIDO at JPL [10]. DriveMaps determines clear paths and obstacles (subsequently used as landmarks) from the stereo pairs of wide field-of-view hazard cameras on the front and back of the rovers. When coupled with onboard

rover components such as accelerometers and wheel encoder inputs, an egocentric map of the environment is built using the DriveMaps response as an index.

The BISMARC ASM for a cache recovery task is shown in Figure 3. The collection of behaviors used by BISMARC

can be broadly broken into two categories: survival (i.e. Avoid Dangerous Places), and task specific (i.e. Scan for Cache). Most tasks will share the same survival behaviors, which allows the rover to carry a set of task behaviors and switch between them if necessary. The survival behaviors include mobility as well as temperature and battery level

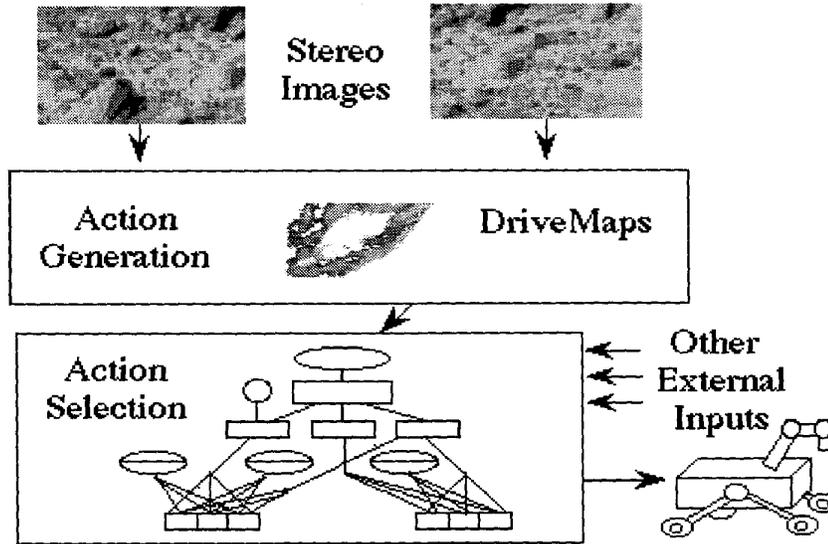


Figure 3 Two level BISMARC architecture with stereo processing, action generation, and action selection subsystems.

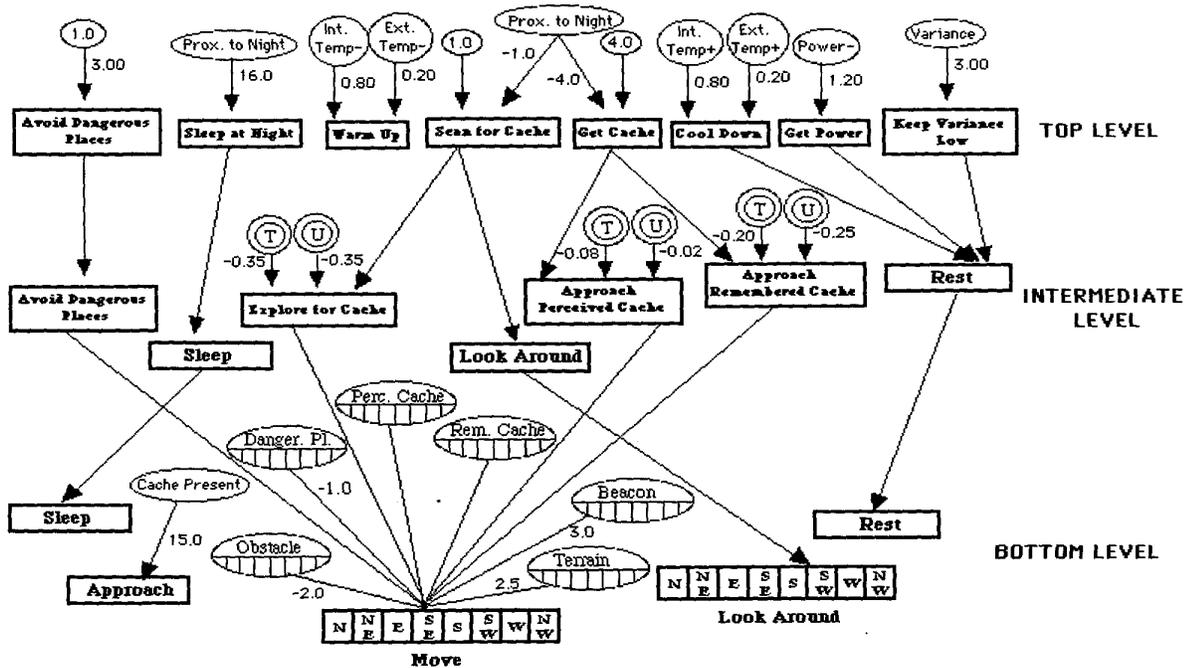


Figure 2 BISMARC ASM for the cache recovery task. The numbers on the links are the weights for the input feed.

preservation measures. Sensor feeds are only done at the appropriate level where needed, which eliminates the potential bottlenecks seen in traditional hierarchical ASMs.

Weights on the links between behaviors perform a type of priority weighting, which will ultimately favor selection of the heaviest weighted action at the bottom level of the hierarchy. For example, the Sleep at Night behavior is the most heavily weighted since absolutely no motion is allowed at night due to the lack of night vision. In the event that sensors such as LIDAR are available, this weighting can be relaxed to allow movement at night. Determination of the optimal set of weights for completion of any task is not mathematically well defined, although recent studies by Pirjanian [19], Yen and Pfluger [25], and Steinhage and Schöner [23] have defined functional definitions of the system dynamics to address this point.

Combination of the weighted links is done in three ways: additive, multiplicative, or through a weighted summation process suggested by Tyrrell [24]. At the bottom level of the ASM hierarchy are the actions that are available to the rover. These include movement, surveillance, survival, and task specific actions. The movement and surveillance actions are direction specific, while the survival ones tend not to be so. Once again, as was the case with the high level behaviors, the rover can carry a set of task specific actions, and select the appropriate set when needed.

Tyrrell introduced the temporal penalty (T-circle in Figure 3) to control action that will take an inordinate amount of time to complete [24]. The temporal penalty is derived using the assigned value raised to the power of the elapsed time during the current action. Temporal penalty nodes increase the likelihood of satisfying the overall mission goal in this example of totally clearing a designated area. In addition, the uncertainty penalty (U-circle in Figure 3) is used to control actions that are heavily dependent on external sensor inputs, which are usually noisy and imprecise.

Mapping of a site is based on the use of information taken at multiple levels of detail. This includes descent imagery, remotely sensed imagery such as that returned by the Mars Global Surveyor, range maps from the onboard sensing suites, wheel odometry, and gyro/accelerometer inputs. The descent and remotely sensed imagery is used to build a coarse level map with a 1 meter grid spacing. This is supplemented by a local map with a 5 cm grid spacing provided by the onboard sensing (stereo cameras) at the "landmarks" such as obstacles, cliffs, habitat modules. These areas are mapped extensively and are used for the sharing of navigational information between robots. The map between these features only includes odometry and directional vector information. This method gives a detailed view of the environment where it is needed,

without the storage overhead that would be associated with fine grid coverage of multi-kilometer sized areas such as those found in an outpost.

Since the environment may change due to climatic occurrences such as dust storms, and the actions of other rovers or manned interaction, BISMARC uses a two-level memory system based on perceived short term memory (STM) inputs and remembered long term memory (LTM) storage. Perceptions are compared to the LTM contents using, at best, uncertain rover localization information. Positional variance is used to weight the match to LTM, with a stronger chance of match in areas of low variance. Variance is kept under control using established landmarks such as a lander or habitat module.

Fault detection is built into the ASM using the following form of sensor activation function:

$$A_s = P_d * (1.0 - \text{dist}) * (1.0 - P_u), \quad (1)$$

where A_s is the activation level for sensor S, P_d is the normalized sensor input, dist is the normalized distance to the perceived objects, and P_u is the perception uncertainty. The perception uncertainty is given by:

$$P_u = \text{ABS} [P_d(t+1) - P_d(t)], \quad (2)$$

where $P_d()$ refers to the time separated normalized sensor samples. This expression for P_u experiences a maximum when the sensor input undergoes a full range swing. The perception uncertainty is used for fault detection (high values indicate a possible fault). Sensors with a high uncertainty will have little effect on subsequent nodes. These sensors are flagged, and are allowed to come back on-line if and when the uncertainty stabilizes.

3. EXPERIMENTAL STUDIES

We ran 1000 trials using a random heightfield based on statistical information returned from the Mars Pathfinder mission. The area encompassed about 1 km by 1 km with a grid decomposition resolution of 5 cm at the detailed map level. Each trial had different starting positions and the placement of 4 cache containers was randomized within the area. Three rovers were deployed for each simulated mission: a scout and two retrieval rovers. These rovers had the capabilities of SRR and FIDO respectively. The bandwidth of the communication channel between the rovers is one Megabit/second, which is the same as the modem installed in the current SRR prototype at the Jet Propulsion Laboratory. The top speed on the rovers was set at 25 cm/sec for the scout and 6 cm/sec for the retrieval rovers, which is consistent with the JPL prototypes. In order

to simulate wheel slippage, we set a 15% loss of traction when climbing over a rock or traversing rocky terrain. The battery lifetime was set at one week on all of the rovers and the timestep size for the simulations was fixed at 0.2 sec. All of the rovers were forced to sleep during the night hours of the simulations, since there were no infrared sensors on any of the rovers.

We included a set of possible faults based on a statistical analysis of 200 simulation runs [7]. These faults included loss of one or both stereo cameras in front and back, loss of mobility in one or more wheel sub-assemblies, loss of power regeneration capabilities, loss of one or more wheel encoders, loss of one or more degrees of tilt sensing, and loss of internal temperature sensing capabilities. In the absence of faults the success rate for the cache retrieval task was 98.9%. Faults caused this rate to drop to 16% without fault tolerance, with an increase to 46% with the fault tolerant weight adjustment discussed above.

In another simulation study, we analyzed the site clearing capabilities of a team of six rovers (dozers) that had been modified with a bulldozer-like blade for pushing rocks. A solitary robot can accomplish site clearing if all of the significant rocks are within the size and mass constraints that the robot is able to handle. Rocks that are outside these limits will need to be cleared using a cooperative multiple robot strategy. This strategy is based on an ant food transport study done by Kube and Bonabeau [15], that includes a recruitment behavior for the case when a single robot cannot move a rock. Call for Help, Broadcast, and Respond to Call behaviors are used to implement the strategy.

We ran 100 trials each with colonies of from two to six dozers using a randomly generated height field. The area encompassed a 50x100 meter rectangle with a grid resolution of 5 cm. Each trial had different placement positions for the rocks, with a statistical profile of the Mars Pathfinder mission site used for mass and number of rocks. None of the rocks were allowed to mass over 175 kilograms. It was assumed that the clearing, staging, and rock pile areas were previously delimited by beacons. In addition all of the rocks in the clearance site are assumed to be clearable (no iceberg effect). Top speed on the dozers was set to 30 cm/sec, with a mass of 100 kilograms, and a size of 2x2x1 meter (length, width, height). Power use on the dozers varied continuously from 30 watts when idle, 60 watts when traveling over open terrain, to 110 watts when involved in pushing the heaviest rock within the dozer's capability when alone. This capability was set to a maximum of 75 kilograms. In order to simulate wheel slippage, we set a 20% loss of traction when pushing a rock. A collision between two dozers was considered as totally disabling to both, and a dozer that was hit by a rock being pushed by another dozer was also considered totally disabled. Each dozer had a forward-facing set of stereo

cameras with a baseline of 25 cm, a spatial resolution of 486x512 pixels, and a 100 degree FOV, a transceiver with a bandwidth of 56 kbaud, and an 8 channel receiver for beacon monitoring.

Success in the simulation studies was measured in terms of total time for the task, and the number of dozers that were healthy at the end of the run. Figure 4 plots the total average time taken for the task versus the number of dozers that were allowed to participate up to a maximum of six. The graph starts at two dozers, since there was always at least one rock within the clearing area that was larger than a solitary dozer could move. The performance was not linear, indicating that there is significant interference between the dozers as the total number increases. This behavior manifested itself through more collisions with rocks being pushed by another dozer, more complicated repositioning operations due to the "avoid other robots" behavior, and travel time delays due to the need to maintain a safe distance during the recruitment phase. The rock-dozer collisions were caused by rocks dynamically approaching the about-to-be damaged dozer from an angle outside the

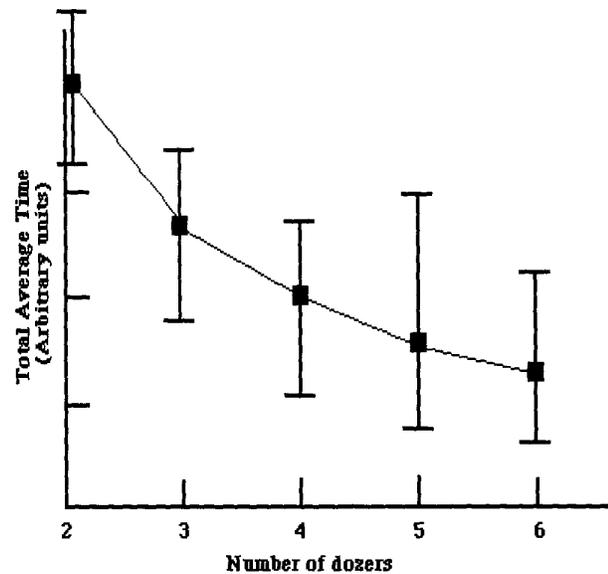


Figure 4 Average total mission times for 500 simulation trials versus the number of dozers in each trial. Time is in arbitrary simulation units with an average time of 3 weeks, 4 days for two dozers. Standard deviations are shown as error bars range of the forward-facing stereo hazard avoidance cameras.

4. CONCLUSIONS

This paper has presented a behavior-based system called BISMARC, which is being evaluated for autonomous

control of mobile robots in planetary surface outposts. The system has shown itself in 1500 simulation runs to be capable of successfully completing complicated multirover missions. Although optimality can not be guaranteed using only a behavior-based control system, planning behaviors can also be included in the ASM hierarchy. Fault tolerant adaptation of the weights in between the behaviors has extended the system for long duration capabilities such as the 4 year Mars outpost mission being considered for a launch in 2007. We are currently porting the algorithm to SRR at JPL, and will begin studies within the next few months into cooperative control of two rovers for transporting a solar tent array container to a site prior to deployment. Our earlier study has identified an electrical power system as one of the most important components for early deployment for outpost operations [13].

5. ACKNOWLEDGMENTS

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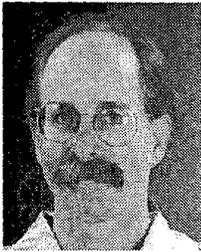
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Technology Rover Design, Integration, and Field Test R&D efforts ("ET Rover/FIDO" -- a Field Integrated Design & Operations rover prototype supporting the NASA Mars '03-'05 sample return missions, and related terrestrial mission simulations), as well as new NASA tasks on use of cooperating robotic assets/rovers for Mars exploration and future human habitation. Schenker also recently led JPL's Planetary Dexterous Manipulators R&D under NASA funding, work that prototyped a robotic sampling concept that flew on the NASA Mars Polar Lander mission. Schenker's other recent robotics R&D activities include a role as founding co-PI for NASA/MicroDexterity Systems Inc.'s development of a Robot Assisted Microsurgery ("RAMS") high-dexterity tele-operative workstation and a longer standing involvement in various tele-robotic technology and system developments for orbital servicing and autonomous robotic exploration. Schenker is a member of AIAA, IEEE, and SPIE; he is a Fellow and 1999 President of the last. He is widely active in external technical meetings, publications, and university collaborations in the areas of robotics and machine perception, having contributed about 100 archival articles to same. Dr. Schenker received his B.S. in Engineering Physics from Cornell University, and completed his M.S.,