A Comparative Study of Teleoperated and Autonomous Task Completion for Sample Return Rover Missions

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Abstract—**This research is aimed at identifying a minimal set of shared control behaviors that would optimize the execution of high-level tasks in terms of robot capabilities and operator engagement in sample return missions. Previous robotic missions to the Moon and Mars, such as Mars Science Laboratory, have relied on supervised autonomy and teleoperation with latency mission scenarios. While this has proven to be an effective approach especially with regard to minimizing mission risks, its scalability to multi-rover systems controlled by a single-operator poses challenges as meticulous planning on daily mission objectives is required and mission success relies heavily on robust, low-latency communication channels. As missions evolve to include multiple robotic platforms exploring celestial bodies farther than Mars, a paradigm shift in mission design approach is required. While completely autonomous exploration rovers may someday be commonly utilized, we aim to show that selectively adding high-level shared control behaviors to execute a sample return mission can significantly improve efficiency at an acceptable addition of risk and complexity.**

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1. INTRODUCTION

Over the last several years, WPIs Robotics and Intelligent Vehicles Research (RIVeR) Laboratory has implemented three different Earth analog planetary exploration rovers to compete in the NASA RASCAL Robo Ops competition and the NASA Sample Return Robot Centennial Challenge. Oryx 1.0 and 2.0 are rugged four wheel teleoperated rovers in a differential-drive skid steer configuration with simple 2-DOF manipulators and bucket scoops. Oryx 2.0 includes a passive averaging rocker suspension allowing it to climb over significant obstacles. [2] The Autonomous Exploration Rover (AERO) is the newest rover consisting of a Husky A200 platform with a 6-DOF Kinova Jaco manipulator, two stereo camera pairs, LIDAR, and fiber optic gyro based IMU. [8]. Oryx 1.0 and Oryx 2.0 have been used in three separate teleoperated competitions, and AERO has been used in one autonomous challenge providing valuable information on mission tasks that are best achieved autonomously or teleoperated.

We identify and compare a number of approaches that have been reported in literature and could be utilized in future missions such as teleoperation, teleoperation with latency, supervised autonomy, shared control, and full autonomy modes of control. This paper outlines the control framework for the Oryx teleoperated robots, the procedures developed for the operators to efficiently, in terms of robot resources and operator input required, execute the mission tasks, and the operator control interface for displaying sensor data to the user. In addition, we describe the autonomous control framework for AERO, the algorithms for searching unknown areas, and the testing procedures to validate the developed autonomy algorithms. Based on the experiences of the Oryx operators and the performance of AERO, we propose semiautonomous shared control behaviors that tasks in a planetary exploration mission would benefit most from added autonomy. For example, behaviors that constrain and simplify multi-DOF manipulator motions could significantly reduce operator load, and lead to more efficient sample pickup or coring operations. Ultimately, behaviors that enable swarm or formation exploring would enable a single operator to control heterogeneous teams of exploration robots.

An emphasis is placed on proposing a minimal set of semi-autonomous behaviors that would allow flexible operation of the rover and ease of memorization for the operator. In addition, because the high-level shared control framework would allow human-in-the-loop control at a task level, a small set of flexible behaviors can be combined by the operator to accomplish a variety of tasks. As exploration missions go farther and become more complex, high-level shared control with emphasis towards fully autonomous exploration will allow the rovers to explore more terrain than ever before in an efficient manner.

2. ORYX 2.0

The NASA RASC-AL Robo-Ops competition is an engineering challenge organized by the National Institute of Aerospace and funded by NASA designed to encourage teams to create teleoperated rover prototypes that can find and pick-up brightly colored rock samples [1]. The challenge is held at the Johnson Space Center rock yard which has analog test areas simulating various terrains similar to ones on the Moon and Mars. The rovers need to navigate a hilly terrain, sand pit, crater field with loose gravel, and rock field with

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large obstacles collecting as many samples as possible within the 1 hour time limit. The competition rules allow teams to control their rovers from their host institution over a 4G cellular radio resulting in limited bandwidth and slight time delays. Time delays up to 1 second and bandwidths as low as 250 kilobits/s are possible, especially if the cellular radio fails-over to 3G, making teleoperation more difficult than in other applications.

Figure 1. ORYX 2.0 collecting a sample rock from the moon-analog crater field at Johnson Space Center Analog Test Facility during the 2012 NASA RASC-AL Robo-Ops competition. ORYX 2.0 collected a total of 13 rocks and one "alien" life-form taking first place in the competition.

ORYX 2.0, shown in Figure 1, is a research mobility platform designed originally for the 2012 NASA RASC-AL Robo Ops competition [2]. Aimed at operating in analog Martian and lunar environments, this rover has passive kinematic suspension with skid steering and is designed to operate on uneven terrain. Even though the passive averaging rocker-bogie suspension with skid steering is not beneficial in all cases [3], it provides ORYX 2.0 with the flexiblity to handle a variety of terrain while maintaining simplicity of the mechanical design. ORYX 2.0 has a footprint of about 1m by 1m with a weight of about 45kg, and with 31 cm diameter wheels is capable of passing over obstacles up to 20 cm high.

ORYX 2.0 is also equipped with a number of sensors. To measure the yaw, pitch, and roll of the chassis, an InterSense InertiaCube3 is used. Feedback on the position of the suspension members is provided by a 12-bit absolute encoder. Finally, drive motors are controlled by Maxon's EPOS2 controllers, which also provide feedback on the wheels' velocity, position, and current draw. Unlike many skid steering rovers, ORYX 2.0 has each wheel driven by a separate motor, making it possible to control the velocity of all four wheels independently.

In addition to sending proprioceptive data back to the operator, ORYX 2.0 carries three cameras on-board to provide visual feedback and situational awareness. A drive camera, mounted on the front chassis member, gives the operator a first-person driving vantage point. A mast camera, mounted on a carbon-fiber mast with pan-tilt unit, enables the surroundings to be quickly scanned and any potential samples identified. Finally, an arm mounted camera assists the operator with sample pickup and storage. Nominally, two operators conduct missions with a primary operator in charge of driving and manipulation, and a secondary operator in charge of finding potential samples and advising the primary operator with additional situational awareness.

3. AERO

The Sample Return Robot Challenge is an annual NASA Centennial Challenge hosted by Worcester Polytechnic Institute for the first time in June 2012. The premise of the competition is to encourage teams composed of engineers, students, and tinkerers to build fully-autonomous robots that can navigate a large outdoor area, find and collect various geologic samples, and return them to the starting pad within the time limit [4]. The caveat is that only space-compatible technologies are allowed, meaning that global positioning systems, sonar, compasses, magnetometers, and similar technologies are not allowed. These limitation create significant challenges to accurate localization and navigation, requiring solutions similar to what many military systems use in GPS-denied or GPS-corrupted areas. Samples for collection are split into three categories, easy, intermediate, difficult, based on how much information and detail is provided on each sample apriori. For example, the easiest samples are fully described, and the difficult ones are just noted to be metallic objects of interest that visually do not appear to belong in the environment.

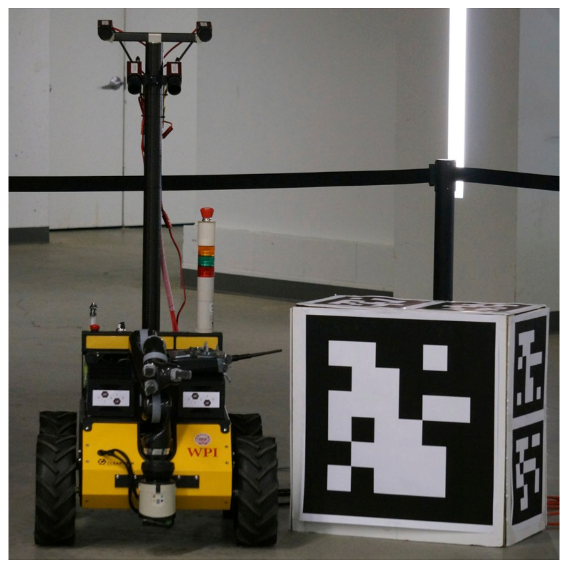

Figure 2. AERO, the Autonomous Exploration Rover, along with its virtual reality homing beacon shown during preparations for the 2013 NASA Sample Return Robot Centennial Challenge.

AERO, the Autonomous Exploration Rover, is a research platform designed originally for the 2013 and 2014 NASA Sample Return Robot Centennial Challenges. Shown in Figure 2, the rover is comprised of a differential-drive four-wheeled mobility platform and 6-degree of freedom (DOF) manipulator with a fixed suspension. AERO has a footprint of about 99cm by 67cm with a mast height of just under 1.5m and weighs about 80kg. While AERO is not able to travel over very rough terrain like ORYX 2.0, it carries more precise sensors and possesses significantly more computation power. AERO is instrumented with four Allied Vision Manta G-095C cameras in a two stereo pair configuration, a KVH

1750 fiber optic gyroscope based inertial measurement unit (IMU), a 50m SICK LMS151 LIDAR, and wheel encoders.

Fusing a combination of data from the LIDAR, IMU, and wheel encoders, AERO implements a simultaneous localization and mapping (SLAM) algorithm to generate a map of the search area without the aid of GPS or compasses. With the map, the rover can split the search area, marking areas that have been searched and generate a plan to explore the uncovered terrain. The lower stereo pair has a shorter base-length designed to help the robot see nearby obstacles potentially missed by the LIDAR and to categorize any samples immediately in front of the robot. The information provided by the stereo cameras helps the rover localize samples very accurately with respect to the base, which is used to move the arm in position to manipulate and store the sample. A second, longer-base length stereo pair is used to identify potential areas of interest to explore. Many samples can be flagged, but not necessarily categorized, up to distances of 20m using the top stereo pair. Once closer, the rover can use its lower stereo pair as described above. Finally, the top stereo pair can locate the home beacon, a box covered in APRIL virtual reality tags [5], at ranges in excess of 50m helping guide the robot back to the starting platform at the end of the search period.

Figure 3. The ORYX 2.0 primary operator graphical user interface (GUI) is shown. Various values such as internal temperatures of components and battery voltages are provided on the left. A large area in the center shows the views from the cameras. The pose of the robot, angle of camera mast, network information, and a small second camera view are all provided on the right. The secondary operator has a very similar GUI, but the mast camera is generally displayed in the center panel. There are few buttons on the GUI, since the robot is primarily controlled with through commerically available gaming controllers with two sticks and multiple buttons.

4. TELEOPERATION WITH ORYX 2.0

Significant amounts of research have been conducted in the previous couple of decades on effective teleoperation. In [6], the authors provide a thorough overview of many of the techniques and challenges in working with a teleoperated system. Many of the challenges, especially the ones associated with time-delay, were experienced during operations with ORYX 2.0. The general teleoperation architecture with ORYX 2.0 for the Robo-Ops competition requires two operators to drive the platform, control the manipulator, and assimilate the proprioceptive and visual data from the rover. All of the data required to maintain the safety of the rover and find samples is available to both operators and both can control the rover if needed. This is functionally similar to the operation of an airplane, where both the pilot and co-pilot have a clear distinction of responsibilities at one period of time, but both have access to the same information and can take complete control if needed. The rover is controlled with commercially available gaming controllers since they provide a very intuitive method to control a skid-steer platform and plenty of buttons for behaviors and action scripts.

The separation of responsibilities between operators usually means the primary operator is in control of the base platform and manipulator. The graphical user interface (GUI) displays either the front-facing drive camera, to drive to a requested location, or the arm-mounted camera, to line up a sample for pickup. The secondary operator is in control of the pan-tilt unit of the mast camera, constantly scanning for potential samples. In addition, the secondary operator helps the primary operator confirm a successful sample pickup and storage using the mast camera. If small corrections during pickup or sample storage are needed and the secondary operator has a better vantage point, they can take control of the manipulator or base and make the adjustment. This arrangement has been experimentally shown to work very well, and in fact during the 2012 competition, there was no period of time that a sample was not either in the process of pickup or in view of the mast camera and secondary operator. The limiting factor for the number of samples cached was the time it took to line samples up and successfully manipulate them.

Several small but very relevant features were implemented on ORYX 2.0 to assist the teleoperation of the platform. By far the most important aspect is to be able to provide the operators of situational awareness during missions. In Figure 3, the camera mast visualization on the right panel of the GUI was implemented to significantly reduce the time to line up a potential sample and improve the communication between the operators. When a sample is found, the secondary operator can immediately tell the primary operator how many degrees they need to turn to line the sample up. The visualization helps the primary operator confirm the information and make a mental note of about how much the platform needs to turn. This process work well, so the sample does not need to be visible in the primary drive camera. If lined up properly, the primary operator can just drive straight forward until the sample enters the field of view and pickup can be initiated. Previous research focused on developing a controller that would keep the robot driving a straight line, even over rough terrain [7].

Sample pickup proved to be one aspect of operations that was especially tricky. Initial testing indicated that lining up the manipulator to the sample and conducting a pickup took excessively long and sometimes resulted in significant forces applied to the end effector due to operator misjudged distances. Figure 4 shows ORYX 2.0 picking up a purple sample along with the clear polycarbonate plate and small piece of tape in the corner. These additions may not seem critical, but the clear plate allows the operator to do two things: (i) align the sample to the scoop and (ii) because the optical properties of the plate change as it bends, the operator receives visual feedback if they are pinching the sample enough to pick it up or if the sample is in the bucket and the scoop is completely closed. In addition, this visual feedback allows the operator to open a small gap in the scoop to drain any extra sand in the scoop without dropping the sample. The small piece of tape in the corner indicates to the operator when they are just barely off the ground helping

Figure 4. ORYX 2.0 picking up a purple sample rock in JSC sand pit. The clear polycarbonate plate and small piece of tape in the corner proved very effective in lining up the manipulator to conduct a pickup operation.

reduce unnecessary wear and tear on the scoop and reduce the amount of extra debris picked up along with the sample. Sample drop off is a completely automated sequence saving the operators time. Once the drop off sequence is initiated, the rover can immediately start driving to the next sample. In the mean time, the secondary operator can confirm a successful pickup with the mast camera.

Overall, the success of the teleoperation depended heavily on how experienced the operators were, and how much time they had to familiarize themselves with the platform. Many of improvements implemented to make operation easier proved critical in efficiently locating and picking up samples. The examples provided here are demonstrated in a relatively simple mission scenario, but the concepts and principles are relevant to teleoperation in significantly degraded conditions.

5. AUTONOMOUS OPERATION WITH AERO

Because of the requirements of the Sample Return Challenge, the algorithms developed for AERO had to function completely autonomously. This is an advantage in some aspects because the algorithms do not need to account for the actions of the operators, but makes the challenge difficult since the algorithms need to flexibly handle a variety of possible scenarios. Several approaches and algorithms we employed worked well, and many did not perform as expected in relatively open and sparse environments searching for samples. AERO's misson can be split into three main subtasks: navigating and localizing within the large outdoor area, identifying and classifying samples, and retrieving the samples with a manipulator.

AERO's navigation system at its core uses the concept of hierarchical control which can be divided into three levels shown in Figure 5 [8]. The supervisor is the top layer of control implemented by a finite state machine and is responsible for mission level task planning and coordinating robot state. Examples of mission-level tasks include searching the field for potential samples, navigating to a located samples, picking up the sample, and returning home. The global planner is the layer of control below the supervisor. It is responsible for planning in a global scale and implementing the mission-task specified by the supervisor. The lowest layer of control is the local planner which generates and follows arc to implement the driving with tentacles algorithm

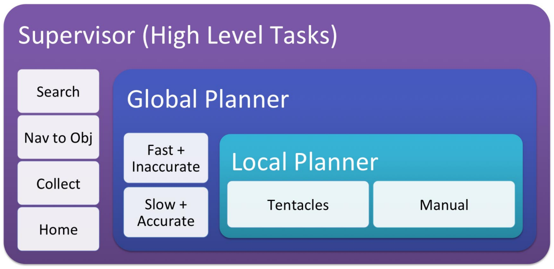

Figure 5. The three levels of the hierarchical control. The supervisor coordinates the mission-level tasks. The global planner plans beyond the sensor horizon on the global map. The local planner plans on a local map representing a snapshot of the current environment around the robot.

described in [9]. The algorithms casts rays in front of the robot and selects to follow a ray that guides the robot to its goal, while avoiding obstacles. By splitting the navigation system into a hierarchial structure as described, the behaviors that require high loop rates and low latency such as obstacle avoidance can be done quickly, while the relatively slow planning phases can be implemented on a longer timescale. This saves computational resources and provides an effective way to navigate and search for samples.

Sample detection and classification is entirely implemented by the computer vision system. The top mast cameras identify anomalies in the grass that could potentially be samples and mark them on a probabilistic map on the robot using very basic RGB threshold filters. The robot inspects each potential sample from a close distance using the fixed, front-mounted stereo vision system. The easy and medium samples are identified and classified using a Linear Binary Pattern (LBP) classifier. Because the features of the easy and medium samples are known ahead of time, the robot is preloaded with a training set of data helping it identify these samples. The hard samples are identified by their generally different appearance in the environment. The metallic hard samples are extracted from the grass background using normalized RGB color filtering. In addition, the fixed forward facing vision system extracts the location, major axis, and bounding box of each sample in order to assist in planning a suitable approach vector for the manipulator.

The Jaco manipulator mounted on AERO has significant complexities with its inverse kinematics because of the specifics of the last three joints on the manipulator. They are designed at a 55 degree angle to reduce the number of potential pinch zones making the manipulator safer to use in unstructured environments. Sample pickup is achieved by locating a sample in image-centric coordinates and then calculating its position in robot-centric coordinates. An inverse Jacobian controller calculates the necessary joint velocities to guide the end effector velocity vector to point towards the sample. A simple PD controller guides the speed that the manipulator approaches the sample. This approach is simple, yet effective picking up several samples during testing.

6. SHARED CONTROL AND BEHAVIORS

A spectrum of control autonomy exists for various robot systems ranging from teleoperation, teleoperation where latency hinders direct teleoperation, supervised autonomy, shared control, and full autonomy. Arguably, shared control, where the user input and various autonomous agents both have control of the system simultaneously is the least understood and studied. Most realizations of robotic systems in reality fall either into the teleoperated or autonomous categories. The rovers currently on Mars implement much supervised autonomy, executing their scripted behaviors autonomously with humans-in-the-loop ready to modify the scripts in case the rovers sense an unexpected issue. Of the few systems that do implement some sort of shared control, few are intuitive or work well. This is not due to deficiencies in the principle, but rather progressive attempts to solve a problem that is very difficult. The principle of shared control, if implemented in an intuitive and transparent manner can significantly improve the ability to search a large, unknown area and find samples of interest.

In [10], Zermelo's navigation problem is used as an example to consider a range of methods as to how shared control may be implemented including traded control, indirect shared control through cues, coordinated control, collaborative control, virtual constraint, and blended shared control. We use these categories as a template to propose a set of shared control behaviors for rovers in sample return mission scenarios that would be useful considering the experiences and approaches that worked well with ORYX 2.0 and AERO.

In traded control, the user and rover can transfer full control of the platform between each other on either an event-driven or schedule-driven schedule. This modality of control would be especially useful while a rover is completing a tedious and monotonous task that happens to include a part that is intricate. The rover can complete the majority of the task by itself, but needs a little help to finish a critical part. A useful behavior during sample pickup might include allowing the rover to autonomously position its manipulator to pickup a sample in a gross manner, and then transfer control to a human operator to fine-tune the grasp and pickup strategy. Once secured by the manipulator, the rover can regain control and autonomously store the sample. The supervised autonomy of rovers as described above is essentially a form of traded control.

Indirect shared control through cues guides the inputs of the operator to ultimately change the behavior of the robot platform. Visual, auditory, tactile, and haptic feedback can all be utilized to implement indirect shared control through cues. In a sample return mission, haptic and tactile feedback could be very useful for the retrieval of samples. One challenge of retrieving samples with ORYX 2.0 is the inability to judges the forces on the end effector and sample well. Haptic feedback could be effective in confirming a good grasp. In addition, the cues can be used to help the operator align the rover base for optimal retrieval position where the operational space of the manipulator is optimal.

In coordinated control, the rover has full control but accepts operator inputs at a lower dimensionality than the task the robot is currently trying to complete. For example if the operator does not care about the orientation of the rover but would like to control the position and minimize the energy required to move the rover, a coordinated control algorithm can accept position inputs from the user and plan motions for the rover that minimize the energy used. This can be further extended by allowing tracking errors of the controllers to vary in different dimensions. For example if the lateral error of the rover is not critical, but the forward position must be carefully controlled, the coordinated controller can take that into account and allow the rover to stray laterally and conserve energy.

In collaborative control, the rover has control of some degrees of freedom while the operator has control of others. This is useful in situations where sample retrieval may be difficult due to poor stability of the platform. The collaborative controller can work to keep the platform stable on the difficult terrain, while the operator can focus on controlling the manipulator to retrieve the sample. Dangerous terrain and situations can quickly mentally overload even the best trained operators. By allowing the rover to autonomously handle a portion of its safety critical tasks, the operator can focus on completing the task quickly and efficiently reducing the risk to the rover.

Virtual constraints are already implemented on many robotic systems, not limited to space systems. In this control modality, certain inputs are not allowed based on the state of the system. In many cases, these inputs are not allowed for safety reasons. For example, a rover can sense when its center of mass is leaving the polygon of stability and tipping is an imminent hazard. The virtual constraint can limit the inputs to allow the rover to travel in the safe direction away from the tipping hazard. Other applications include speed limits or speed minimums depending on the stability or structure underneath the rover. For example, to reduce the risk of sinking in very soft sand, it may be beneficial to drive over the sand relatively quickly until more stable terrain is found. This would have been useful for ORYX 2.0 where it got stuck several times in the gravel craters due to its inability to climb out slowly.

Finally, blended shared control offers a very broad range of possibilities where the operator input and autonomous controllers on board the rover combine their effects on the robot and control the rover simultaneously. The most exciting application for this control modality is allowing the rover to execute certain motion primitive autonomously, but guiding the overall search strategy through the human input. The motion primitives will have to be generated with respect to the high level search patterns or methods that the human commands, but these could be generated offline through massively parallel simulation. This will allow an operator to guide a rover with few inputs, allowing them to efficiently control more than one rover. Consider the possibility of a swarm of exploration rovers where the general behavior of the swarm is controlled by the operator, but each rover is driving itself within the swarm.

The proposed behaviors are by no means exhaustive, but these are a relatively minimal set that given the experiences with ORYX 2.0 and AERO, we feel would significantly improve operations of the sample return rover in Earth analog scenarios.

7. FUTURE WORK

Future work will focus on implementing the proposed behaviors and control modes on a heterogeneous team of robots comprised of ORYX 1.0, ORYX 2.0, AERO, and available quadrotor platforms. High-level goals are provided as inputs by the operator to the shared control architecture and the robots also have some objective such as energy conservation or maintaining a certain orientation. The shared control architecture coordinates and disseminates a common policy to the robots of the team and monitors that the actions of the individual robots are consistent with the global search strategy as shown in Figure 6. Once the architecture is validated in a variety of simulated situations, it can be demonstrated at an Earth analog test site.

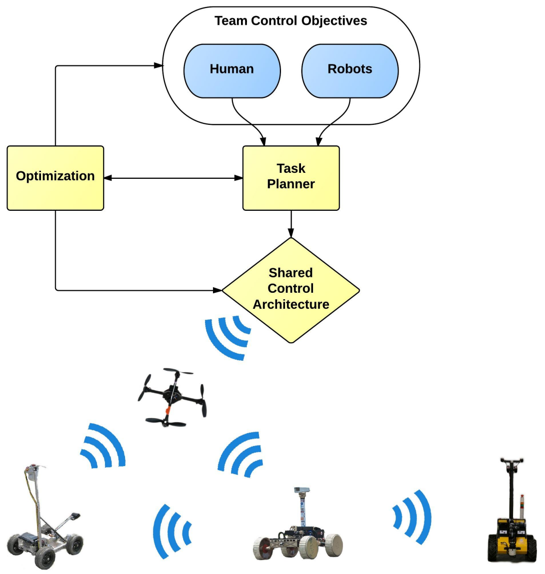

Figure 6. Blended shared control can be implemented in a heterogeneous team of exploration robots to effectively explore a large, unknown area with one operator.

8. Conclusion

We have highlighted the approaches we have used in teleoperated and autonomous rovers in two separate implementations. Based on those experiences, we have proposed a set of behaviors and control modalities, that if implemented would allow shared control of rovers in sample return missions and could significantly improve our ability to efficiently explore large unstructured environments.

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References

[1] Rasc-al exploration robo-ops competition. National Insitute of Aerospace. [Online]. Available: http://nia-cms.nianet.org/RoboOps/index.aspx

[2] J. Amato, J. Anderson, T. Carlone, M. Fagan, K. Stafford, and P. T., "Design and experimental validation of a mobile robot platform for analog planetary exploration," *Proc. IECON 2012: 38th Annual Conf. of the IEEE Industrial Electronics Society*, Montreal, CA, Oct. 25-28, 2012.

[3] T. Thueer, R. Siegwart, and P. Backes, "Planetary vehicle suspension options," in *Aerospace Conference, 2008 IEEE*, march 2008, pp. 1 –13.

[4] Sample return robot challenge. Worcester Polytechnic Institute. [Online]. Available: http://challenge.wpi.edu

[5] E. Olson, "AprilTag: A robust and flexible visual fiducial system," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, May 2011, pp. 3400–3407.

[6] J. Chen, E. Haas, and M. Barnes, "Human performance issues and user interface design for teleoperated robots," *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, vol. 37, no. 6, pp. 1231–1245, 2007.

[7] T. Carlone, J. Anderson, J. Amato, V. Dimitrov, and T. Padir, "Kinematic control of planetary exploration rover over rough terrain," *Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on*, 2013.

[8] V. Dimitrov, M. DeDonato, A. Panzica, S. Zutshi, M. Wills, and T. Padir, "Hierarchical navigation architecture and robotic arm controller for a sample return rover," *Systems, Man, and Cybernetics (SMC), 2013 IEEE International Conference on*, 2013.

[9] F. von Hundelshausen, M. Himmelsbach, F. Hecker, A. Mueller, and H.-J. Wuensche, "Driving with tentacles: Integral structures for sensing and motion," *Journal of Field Robotics*, vol. 25, no. 9, pp. 640–673, 2008. [Online]. Available: http://dx.doi.org/10.1002/rob.20256

[10] A. Enes and W. Book, "Blended shared control of zermelo's navigation problem," in *American Control Conference (ACC), 2010*, 2010, pp. 4307–4312.

Biography

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