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Field Analogue Simulations Investigating EVA/Robotic Collaboration in Lunar Exploration

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By the time that human missions to the moon resume, a half century or more will have passed since the last Apollo missions. Technologies only dreamed of in the days of Apollo will be available to assist, augment, and supplement human explorers on the moon and Mars. However, many of the current conceptualizations of human planetary surface exploration seem to start where Apollo left off, with robotic systems largely relegated to transport functions or operations independent of the human explorers.

Under support from the NASA Lunar Advanced Science and Exploration Research (LASER) program, the University of Maryland (UMd) and Arizona State University (ASU) have teamed up in a four-year effort to investigate advanced collaborations between space-suited humans and robots for lunar exploration. This investigation is focused on a series of annual field trials in the Arizona desert, wherein planetary geologists will serve as simulated astronauts using advanced space suit simulators and dexterous manipulator-equipped rovers created by the UMd/ASU team. In an homage to the long-standing NASA Desert Research and Technology Studies (RATS) test series, this stand-alone research investigation has been named the Desert Field Lessons in Engineering And Science, or Desert FLEAS.

This paper covers the concept behind the Desert FLEAS research, and details the evolutionary set of annual field trials with increasing space suit and robotic system capabilities. In an early test series in September 2010, the UMd MX-A space suit simulator was paired with the Robotic Assist Vehicle for Extravehicular Navigation (RAVEN) astronaut assistance rover developed by the combined senior capstone design classes of the UMd Aerospace Engineering department and the ASU School of Earth and Space Exploration. In this proof-of-concept test, the MX-A suit was equipped with head-mounted displays with head-tracking sensors for hands-free gestural interface to an information data base, along with several approaches for EVA control of the RAVEN driving functions. These tests, performed on the ASU campus and in conjunction with the 2010 NASA Desert RATS tests at the Black Point Lava Flow, Arizona, included EVA-directed remote sampling via the RAVEN dexterous manipulator, and human/robot paired traverses across the analogue site.

In the first formal LASER test series, the UMd/ASU team spent a week performing field trials in March, 2011 at the Warford Ranch volcano field in southwestern Arizona. In

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daily traverses, the research team investigated the use of advanced controls and displays in the new MX-B space suit simulator to provide the scientist-wearer with access to advanced geological exploration tools, such as a hand-held microscope, via the head-mounted displays internal to the helmet. At the same time, gestural and voice commands were examined for their efficacy in directing the navigation of the robotic support vehicle.

This paper reports on the results of the first two Desert FLEAS field trials in support of the LASER program, with lessons learned from these tests driving the development targets for the second year of field tests in May, 2012. Plans for future Desert FLEAS activities include the use of MX-3, an actual pressurized suit as compared to the passive simulation of the MX-A/B series of suits. In addition, subsequent years will focus on the development of advanced robotic capabilities and operator interfaces, including the deployment of a new robotic support vehicle for future analogue field trials.

Acronyms

ASU	Arizona State University
ATV	All Terrain Vehicle
D-FLEAS	Desert Field Lessons in Engineering and Science
D-RATS	Desert Research and Technology Studies
EVA	ExtraVehicular Activity
HD	High Definition
HMD	Head Mounted Display
IMU	Inertial Measurement Unit
LASER	Lunar Advanced Science and Exploration Research
MX	Maryland eXperimental (suit systems)
NASA	National Aeronautics and Space Administration
PLSS	Portable Life Support System
RASC-AL	Revolutionary Aerospace Systems Concepts - Academic Linkage
RAVEN	Robotic Assist Vehicle for Extravehicular Navigation
RDF	Radio Direction Finding
RF	Radio Frequency
ROS	Robot Operating System
RRC	Remote Rover Controller
RWC	Rover Wrist Controller
SSL	Space Systems Laboratory
TLX	(NASA) Task Load Index
UMd	University of Maryland

I. Introduction

The underlying concept of this study is to perform field simulations of planetary surface science investigations in relevant analogue environments on Earth, and to test different operations concepts to determine efficacy and science productivity of each operational approach. Thus, a surface geochonologic (geological age measurement) exploration task might be performed in shirtsleeves as a control, then again in a pressure suit for pure extravehicular performance, then with robotic assistance, and finally in a fully robotic mode. In this way, each operational concept will be directly compared to the other viable candidates to determine which produced the best science return as a function of time, operator workload, or other metrics of interest.

A particular focus for this research is the use of advanced robotics in support of human planetary surface exploration. The Apollo experience was essentially entirely EVA-based, with the use of a rover solely for crew and equipment transport. The NASA Desert Research and Technology Studies (RATS) program performed a pioneering series of tests of an astronaut support rover (ASRO) and the EVA Robotic Assistant (ERA) vehicle starting in 1999, which illuminated the essential requirement that robotic systems must (at the very least) not add to the crew's workload or result in slower overall traverses (Figure 1).[1] Later Desert RATS field analog studies tested the "Electric Tractor" as an EVA-crew controlled robotic system, capable of pulling science packages and local site preparation through grading and digging adapters.[2] Recent Desert

RATS tests have examined the use of the NASA Ames K-10 robots for pre- and post-EVA site evaluation, but real-time EVA-robotic operations in recent years have focused on the use of a small pressurized rover as the crew support vehicle.[3] As shown in Figure 2, following EVA crew closely with a pressurized rover can be a burdensome task, resulting in relatively long traverses away from the rover, and requiring the crew to carry all their own tools and samples for these surface operations. This observation led directly to the central focus of this study, in which a small "personal" rover follows the crew closely and provides support specifically focused on augmenting surface science.

Figure 1. Electric Tractor at 2004 Desert RATS

Figure 2. EVA operations from pressurized rover (2009)

II. Test Infrastructure

Obviously, to simulate cooperative EVA/robotic planetary surface exploration in field analogue tests, it is necessary to have functional simulations of both pressure suits and appropriate robotic systems. The initial approach to this project featured components which were already in hand at the University of Maryland under a combination of discretionary funding and through senior capstone design courses sponsored by the Maryland Space Grant Consortium.

A. Planetary Surface Spacesuit Analogues

Although the University of Maryland Space Systems Laboratory (SSL) has been developing and testing full pressure suits for over a decade,[4] it was felt that a pressurized suit would not be feasible for the early stages of this program. Pressurized suits, particularly with a self-contained life support system providing pressurization and cooling, are heavy enough to make prolonged operations at full Earth gravity an unrealistic representation of the physiological demands of mobility on the Moon or Mars. While the SSL is in the early design stages of a full pressure suit specifically designed for 1-g field tests, the initial field testing process was based on the use of unpressurized suit simulators to replicate EVA conditions.

The unpressurized suit simulators used for these tests to date are shown in Figures 3 and 4. MX-A ("Maryland eXperimental suit-Alpha") was the first suit in a planned series of unpressurized suit simulators, intended specifically for full-gravity field testing. MX-A is a two-piece waist entry suit, using bulk material to roughly replicate the constraints of a pressurized suit. Although used successfully, it was replaced by MX-B ("Bravo"), which is a single-piece torso-entry suit designed to accommodate a wider range of test subjects, while reducing repair and maintenance requirements. Both suits used ellipsoidal bubble helmets attached to the backpack to facilitate the integration of vent air, communications, and experimental technologies to be assessed in the field trials. More details on these suit simulator systems are available in reference.[5]

B. Astronaut Assist Rovers

During the 2009-2010 academic year, the senior capstone design classes in Aerospace Engineering at the University of Maryland and Space Exploration at the Arizona State University teamed up to design an

Figure 3. MX-A Suit Simulator (2010)

Figure 4. MX-B Suit Simulator (2011)

astronaut assist rover, named the Robotic Assist Vehicle for Extravehicular Navigation, or RAVEN. This project consisted of the paper design of a lunar vehicle, and the actual design and construction of a vehicle for Earth analogue testing. The RAVEN vehicle was rolled out on April 23, 2010, and subsequently tested for suitability for field testing.

The design of the RAVEN rover was a classic case of over-constrained design. The lunar vehicle was designed to be as light as possible, in keeping with use on a sortie-class lunar exploration mission. To this end, the vehicle was designed with a three-wheeled chassis to save weight. While the intent for the Earth analogue vehicle was to produce a vehicle similar to and equally capable to the lunar design, the physical development process was severely limited in budget ($5000) and time (six weeks from start to roll-out). To meet these constraints, the all-wheel drive and actively steered configuration of the lunar vehicle was modified to a free-swiveling passive rear wheel, which reduced operating requirements to two actively-controlled wheels with differential drive to accomplish steering. While this limited available drawbar pull, the intent was to develop a vehicle capable of climbing at least 20^{o} slopes on Earth.

Figure 5 shows the initial operational configuration of RAVEN in September 2010, reflecting the changes to the basic configuration based on the initial series of checkout tests on the UMd campus since rollout. The vehicle was equipped with a six degree-of-freedom dexterous manipulator from the UMd Space Systems Laboratory, and had two sensor arches which manually folded down for transport. RAVEN was built at the University of Maryland, and was transported to Arizona State University prior to the first field trials, where additional sensors were integrated onto the vehicle. Between the first and second field trials, RAVEN remained at ASU, where the electrical system was upgraded and the software converted to ROS, an open-source robot operating system. Some minor configuration changes also were made, such as the removal of the aft sensor arch and addition of warning lights to signify system functionality to those in the vicinity (Figure 6).[6]

III. Field Tests

As proposed to the NASA Lunar Advanced Science and Exploration Research (LASER) program, the University of Maryland and Arizona State University have envisioned a multi-year program of technology development activities, focused on annual field trials to assess the functionality and impact of the development products. This series of tests is similar in nature, but markedly smaller in scope, to the NASA annual Desert Research and Technology Studies (Desert RATS) field trials. In homage to the NASA activity (and with a wry appreciation of the difference in size), the UMd/ASU field trials have been dubbed the Desert Field Lessons in Engineering and Science (Desert FLEAS) tests.

Figure 5. RAVEN Astronaut Assist Rover (2010 configuration)

Figure 6. RAVEN (2011 configuration)

A. Desert FLEAS I - September, 2010

Although before the official start of the NASA grant, an opportunity arose to have an early field trial of the Desert FLEAS system in September 2010. The combined senior capstone design classes of UMd and ASU which created the RAVEN rover were awarded first place in the undergraduate division of the NASA Revolutionary Aerospace Systems Concepts - Academic Linkage (RASC-AL) student design competition. Since the prize consisted of financial support for taking the students to the final day of the 2010 Desert RATS tests, the team decided to also bring RAVEN and the MX-A space suit simulator, and thereby take advantage of the opportunity to do one day of testing at the Desert RATS site, as the culmination of a week of final integration and testing on the ASU campus.

1. Systems Checkout

The Desert FLEAS I tests began with unpacking, reassembly, and checkout of the RAVEN vehicle from the cross-country trip from UMd. The sampling manipulator, a reconditioned six-degree of freedom (DOF) robot arm originally developed in the SSL for neutral buoyancy operations, was equipped with a simple sampling scoop and integrated on RAVEN. A number of advanced avionics systems were developed and added to the MX-A suit simulator in support of this test, including geological instruments (a handheld digital microscope), command and control systems for directing RAVEN in the field, and a remotely-controllable head-mounted display for the suit wearer. Although designed jointly by senior students in capstone design courses at UMd and ASU, RAVEN was built at UMd; five days on campus allowed the ASU students to integrate some of their science instrument hardware and get familiar with rover operations.

2. Field Demonstration at NASA Desert RATS

Following a week of checkout at ASU, all of the Desert FLEAS systems were transported to northern Arizona for the academic open house on the last day of Desert RATS 2010. After setting up the ground station and protective canopy, the RAVEN rover was checked out on site. The primary command and control communications mode (802.11 network) proved to be unworkable due to powerful interference from the NASA site wireless infrastructure. RAVEN operations for the first half of the day were limited to a short-range wireless X-Box controller, and a hard-wire Ethernet command link for manipulator operations.

After initial trials, a UMd subject in the MX-A suit simulator did a local traverse on foot accompanied by RAVEN. No attempt at geological exploration was made during this test; the primary focus was on remote control of RAVEN and verifying its ability to keep up with the suited subject at normal walking speeds (Figure 7). Periodic stops in the traverse allowed assessment of the subject's ability to reach various locations on RAVEN, looking ahead to rover functions such as transporting tool carriers and sample stowage. This traverse covered approximately a kilometer and took approximately 45 minutes. With the seasonal weather at the site (highs in the mid 90's), this was felt to be a conservative limit on MX-A operations due to subject overheating. One conclusion from this experience was the need for thermal control, even in unpressurized suit simulators.

RAVEN then moved on to a test sequence operating the sampling manipulator at a dirt pile at the Desert RATS base camp. As mentioned above, this had to be done under hard-wired communications due to wireless interference. RAVEN's sampling manipulator, even though limited to a simple scoop as an end effector, was able to take controlled samples of both regolith and small (3 cm) rocks, and to perform simple excavations (Figure 8).

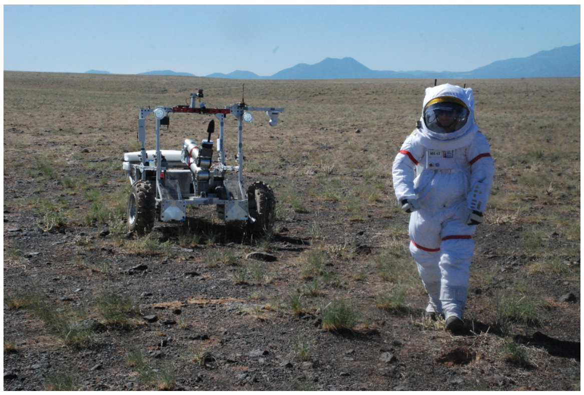

Figure 7. RAVEN in traverse with EVA subject in MX-A suit simulator

Figure 8. RAVEN performing robotic digging and sample collection tests

In the afternoon, as the NASA systems were powered down and Desert RATS personnel started packing, radio frequency interference decreased to the point where reliable 802.11 communications could be established with RAVEN. Taking advantage of this opportunity, RAVEN did a second traverse, controlled alternately from the MX-A suit backpack (worn without the simulated pressure garment due to thermal concerns) using both head-tracking and wrist touchpad control, and remotely via the hand-held game controller. The visor containing the head-mounted displays could be remotely commanded to flip down in front of the test subject's eyes, or to flip up and out of the line of sight, via commands on the wrist touch pad. Accelerometers in the same visor assembly allowed the control of RAVEN via head tilt forward/bask for forward speed, and head tilt side-side for turning rate. Discrete buttons on the wrist-mounted touch pad performed the same functions for manual RAVEN control. By sensing which finger engaged a button via a sequential electronic polling system, the pad allowed multiple definitions for each button without mode switching. Thus, the same forward/back/left/right set of buttons could command the rover motion and camera pan-tilt at the same time, depending on which finger was used to touch the button pad.

This traverse was approximately two kilometers, and took approximately 90 minutes, including extended stops for photo opportunities. As daylight ended, RAVEN and all associated Desert FLEAS hardware were packed for the return trip to ASU.

3. Lessons Learned from Desert FLEAS I

- Active cooling is critical for extended suit operations at elevated temperatures, such as those typical of the north Arizona desert in September
- Radio frequency allocations are necessary for complex simulation sites
- Multiple redundant communications paths (particularly umbilical-based hardwire) allow continued testing even in the event of RF interference
- The free-swiveling rear wheel is of limited utility, and is particularly disadvantageous in cross-slope traverses
- RAVEN is appropriately sized to provide easy interaction with a suited subject, and is easily capable of keeping up with the fastest nominal walking traverse

- The servo-controlled head-mounted display worked well to provide high-resolution video when needed, and cleared the subject's field of vision when not in use
- The finger-specific button selection was prone to errors, particularly in moments of time-critical commanding
- Head-tracking command of rover motion worked well and produced excellent control of fine inputs, but required strange and prolonged head poses with awkward view angles to the robot

B. Desert FLEAS II - March, 2011

The first LASER-supported Desert FLEAS test was conducted the week of March 21-25, 2011. This test was intended to examine potential roles for an astronaut assist rover in support of geological exploration in a lunar-relevant analogue location. For the first focused test session, the Project Scientist of the D-FLEAS team selected the Warford Ranch area in southwestern Arizona. This area has a number of shield volcanos with exposed lava flows, and offers an appropriate level of terrain features for an initial test series. This site has been used for geological familiarization activities with a number of NASA personnel, including newly selected astronaut candidates. The test was scheduled for March, to take advantage of favorable weather and comfortable temperatures at that time of year in southern Arizona.

1. Remote Operations and Systems Checkout

After two days of testing and checkout at ASU, the team headed to Warford Ranch for three days of testing in the field. The first day of activities was dedicated to rover operations, while the science personnel scouted the local area for sites of geological interest for science data collection studies the next day.

RAVEN was originally designed to climb slopes of twenty degrees. In initial testing at UMd, it successfully traversed slopes in both directions nearing forty degrees; however, all available test areas were covered in grass. During the checkout phase of Desert FLEAS I the previous year, RAVEN successfully traveled up and down slopes nearing twenty degrees, but these were also grass covered. These same moderate slopes proved too much for cross-slope travel, as the free-swiveling aft wheel could not supply sufficient transverse force to hold the tail of the vehicle up the hill. As a result, when a critical amount of weight transferred to the downhill drive wheel, the uphill drive wheel slipped, allowing the rover to turn its back end straight down the slope and roll or slide backwards. Thus, entering Desert FLEAS II there was a real question about the ability of RAVEN to traverse slopes, particularly with realistic soil properties.

In desert testing on surfaces of packed sand and small rocks, RAVEN proved incapable of climbing hills greater than ten degrees. At steeper slopes, the drive wheels dug into the surface of the soil, requiring the operator to drive out down-slope to recover. The basic terrain at this site was a series of plateaus or terraces, with slopes to dry washes of varying steepness. While there were generally access paths within the capability of the existing RAVEN configuration, the flow channels of the dry washes were often bounded by several feet of near-vertical slopes, forming impassable barriers for extended RAVEN traverses. A nearby cliff of exposed layering was chosen as the prime science site, and RAVEN did successfully traverse through the local terrain including crossing a dry wash to reach the science site from the base camp.

2. Geology Survey Tests

The central focus of this program is to rigorously address the potential functionality of robotic systems to increase human performance in geological exploration activities. To this end, the second day of testing was focused on geological traverses, with and without rover support.

Two test subjects were used alternately throughout this test protocol. One is a highly experienced field geologist; the second is a graduate student in geology who has relatively extensive field experience, including involvement in past Desert RATS tests. Each subject did three surface traverses in the same order: in shirtsleeves, wearing the MX-B suit simulator, and wearing MX-B while accompanied by the RAVEN rover (Figure 9). To accommodate the limited slope capability of the current rover configuration in the local soil conditions, the final exploration task selected was aimed at categorizing the geochronology of terraces created by historic drops in water levels. Each of the six geological activities took place on a separate terrace, averaging 1-2 meters above the local plain. Erosion ramps provided access for RAVEN to come to the test subject, or for the suited subject to easily walk to the rover to take tools or deposit samples. Each terrace was approximately 20-30 meters in length and 5-7 meters in width. The exploration task started with the subject walking around the perimeter of the terrace, making verbal notes on the geology and identifying likely targets for sampling. The established protocol was then to obtain three samples suitable for geochronological dating using a rock hammer (Figure 10); completing the sample collection was the final step for that test session. The average time for completion of the complete test sequence was 10-15 minutes.

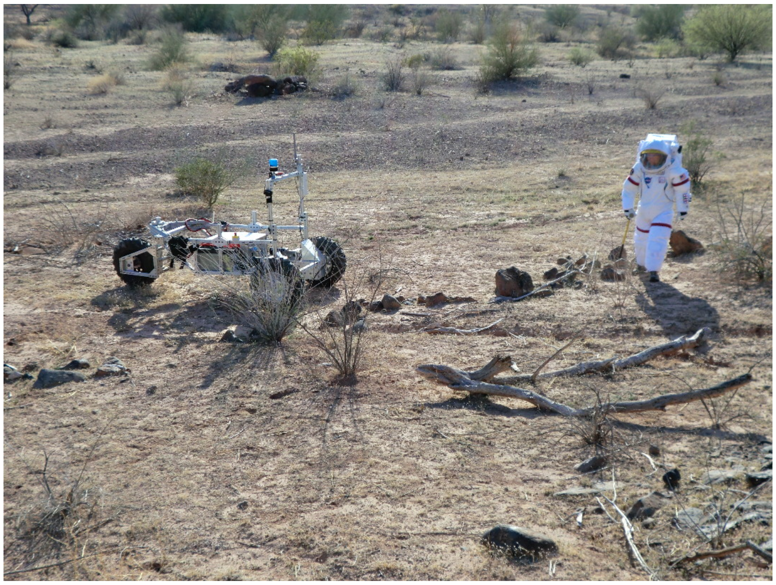

Figure 9. RAVEN supporting EVA subject

Figure 10. Suited subject performing sampling using a rock hammer

At the end of each test, the subject rated the difficulty of the test case using the NASA Task Load Index (TLX) rating scale. As is typical,[7] the overall process was rated on a 0-100 scale in each of six categories: mental workload, physical workload, temporal pressure, overall performance, total effort, and frustration level. The ratings of the two subjects are illustrated in Figures 11 and 12.

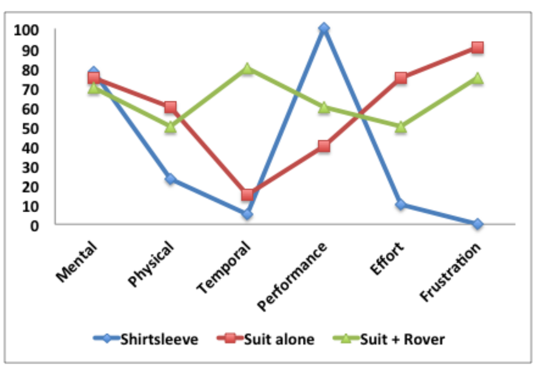

Figure 11. NASA TLX ratings for experienced field geologist

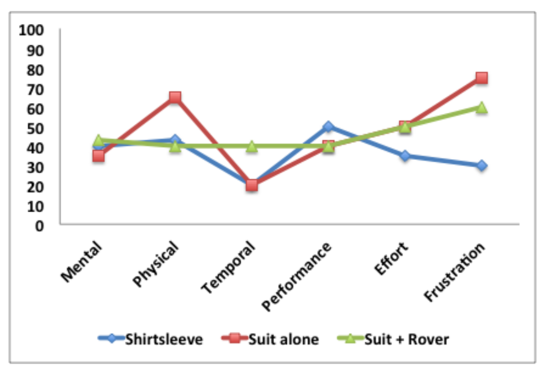

Figure 12. NASA TLX ratings for geology graduate student with Desert RATS experience

The TLX results reveal that neither test subject experienced a noticeable difference in mental workload between any of the test conditions. Other than that criterion, the shirtsleeve operations were, as expected, rated superior to the other two cases across the board. Suited operations required higher levels of effort across the categories, but interestingly enough, the addition of the rover mitigated test subject demands in the categories of physical workload, total effort, and frustration levels. The additional tasks associated with controlling the rover (which was limited to direct teleoperation in this early test series) did lead to that test condition rating as most demanding in the category of temporal demands, but both subjects rated the suit

+ rover combination as less frustrating and less total effort than the suit alone.

3. *Night Science Operations*

Any moderate-length mission to the Moon would involve part or all of a lunar night. Rather than shut down exploration activities for 14 days until local sunrise, it is likely that exploration systems will be developed to enable operations to continue throughout the lunar night. During Desert FLEAS II, a night run was conducted to start to assess design features required for night operations.

The MX-B suit was outfitted with high-intensity LED lights for illumination of the optimum two-hand work envelope in front of the wearer's torso, and of the path ahead for walking. A flashing beacon was also added to the top of the simulated portable life support system (PLSS) for ready identification of the test subject's location in the dark (Figure 13). Halogen headlights were also integrated onto RAVEN for purposes of driving and illumination of the suited subject's exploration area (Figure 14). RAVEN was modified for this test with a sunlight-visible blue strobe light to warn those in the test area when the vehicle is powered up; it was found that this strobe overpowered all other lighting and destroyed the night vision adaptation of personnel in the area, so it was disabled for this night test.

Figure 13. MX-B with Area Illumination and Tracking Beacon

Figure 14. RAVEN with Headlights for Night Operations

No quantitative metrics were attempted in this test. Real-time and post-test evaluations by the geologist-test subject revealed that the provided lighting was adequate for full geological exploration in the local area, and for safe identification of a walking path in the presence of terrain obstacles. The suit headlights were much lower in intensity than those on the rover, but the subject generally used the suit lighting rather than taking the time to command the rover to point its lights into the area in which she was exploring. The suit headlights were inadequate to provide acceptable video of the subject's activities using the helmet-mounted HD video camera, but the rover lights provided more than enough illumination for the same model camera mounted to the rover. Rover lights were adjusted so that one provided illumination right in front of the vehicle ("low beams") while the other illuminated the far field ("high beams"); the video camera clearly documents an underilluminated region between the two spots, although this was not overtly noticeable in real time to the support personnel accompanying the vehicle in the dark.

4. *Lessons Learned from Desert FLEAS II*

- A new rover, with a completely different chassis configuration, will be necessary for trafficability on the terrain selected for the later field trials in this program

- Field geologists in simulated pressure suits routinely traverse thirty degree slopes in all directions in pursuit of science targets
- Subjective evaluations rate rover support for suited EVAs to be beneficial in terms of both total effort and subject frustration, but it does add complexity which can affect time-critical task performance
- A wrist cuff-mounted miniature joystick proved to be highly beneficial for routine RAVEN teleoperation by the suited subject
- Night operations are both feasible and scientifically productive, but equipment (especially suit interfaces and lighting) needs to be designed in from the outset, rather than being added in as an afterthought

C. Plans for Future Field Tests

Under the current plans, Desert FLEAS III will take place in May-June, 2012 at the SP Volcano in northern Arizona. This site, also used by the ongoing Desert RATS tests in September of each year, will provide a wealth of active science targets with terrain which is largely accessible within the limitations of the existing RAVEN vehicle. The choice of a May-June date avoids conflicts with Desert RATS, should provide more moderate weather, and fits well into the academic schedules of UMd and ASU.

In March of 2013, Desert FLEAS IV will focus on the Superstition Mountains near Phoenix. This site, which has increasingly ambitious terrain features, will require the development of a next-generation robotic vehicle to support the LASER testing. This advanced rover is currently planned to feature fully articulated suspension, and the capability to support dexterous telerobotic operations while simultaneously allowing the suited test subject to ride on the rover to reduce physiological workload due to walking between sites. This test is also planned to be the field testing debut of MX-3, a fully pressurized suit to increase EVA fidelity and to incorporate advanced informatics for the wearer.

The final planned test series for this research grant will be Desert FLEAS V, which will take place in 2014 at South Mountain in Phoenix. Although within view of the ASU campus (and providing easy logistics for daily operations), the South Mountain site will be by far the most demanding in terms of terrain and test complexity.

IV. Future Work

To complete the planned four-year sequence of field tests, a number of system upgrades will have to be made on a yearly basis. In both the rover and suit areas, next generation versions of the test hardware will be essential for continual enhancement of analogue fidelity and quantitative data collection.

A. Next Generation Rover

As was discussed earlier, the three-wheel configuration of RAVEN with a free-swiveling rear wheel was selected both to minimize mass of the flight vehicle design and to reduce costs for the Earth analogue rover. Given the problems of both cross-slope stability (caused by gravity loads on the free-swiveling rear wheel) and slope angle limits (controlled by limited drawbar pull with only two driving wheels), the next generation RAVEN vehicle is currently under design in the UMd Space Systems Laboratory.

The current design activity is focusing on a four-wheel independent suspension/independent steer chassis for future EVA-assistant robots. All-wheel drive will significantly increase drawbar pull for better slope climbing capability, and independent all-wheel steering will allow greater control on steep cross-slope traverses. Trafficability will also be improved by the use of independent suspension elements which are designed to continually reallocate weight profiles across the vehicle's wheels in rough terrain.

A further requirement driving the redesign is to enhance the accommodation of advanced mission elements on the rover. In brainstorming sessions with field geologists, the rover design team began to differentiate between a "mule" rover which just serves to carry science instruments, tools, and samples for the pressure-suited geologist, and the "grad student" rover, which can be relied upon to fully document rocks of interest to the human geologists, perform sampling, and log and curate the samples pending a return to base. By enhancing the number and dexterity of rover-mounted manipulators and interchangeable end effectors, along with increased levels of command autonomy, we will strive for the "grad student" level rover for future tests.

B. MX-3 Pressure Suit

While the use of space suit simulation garments has been completely adequate for the first series of tests, it is clear that the fidelity of the analogues to flight suits (or to currently undefined surface exploration suits) is limited, which impacts the results gained from the simulation. MX-A and MX-B provide greater flexibility than would be present in even the best pressurized suits, and manual dexterous tasks involving hand grasps are significantly less prone to muscular fatigue than a "conventional" pressure suit.

To this end, the SSL is developing MX-3, the third in a series of "Maryland eXperimental" fully pressurized space suit simulators. Unlike the first two pressure suits in the MX-series, which were optimized for neutral buoyancy operations, the MX-3 will be designed from the outside as a pressurized suit for Earth analogue field tests. This suit will provide a much higher fidelity environment across the board for future Desert FLEAS test subjects, by replicating a flight pressure garment at the same suit pressure.

Two challenges exist for the development and deployment of MX-3 for future testing: pressurization and thermal control at a reasonable weight level. Both functions typically performed by the portable life support system, pressurization can take advantage of the ubiquitous availability of air on Earth to provide design pressure (3.5 psid) at the nominal flow rate (6 CFM) through the use of a small centrifugal compressor. Cooling represents a more difficult target, however, as sublimation cooling does not function in an appreciable atmosphere, and heat sink approaches (such as carrying a block of ice for wearer thermal comfort) are prohibitively expensive in mass-on-back for extended periods of time. A series of experimental investigations is already underway to evaluate possible solutions to these design challenges.

V. Conclusions

Two highly successful field tests in the first six months of this program have demonstrated clearly the benefit of a small, focused analogue test program. The experimental and logistics demands of analogue field testing can be challenging, but the opportunity to conduct field simulations of planetary surface exploration is highly motivating to the participants, particularly the students. The structure of Desert FLEAS, with direct intermingling of science and engineering teams to enable science-driven field testing of advanced technologies, has greatly augmented the educational value to the student team members from both UMd and ASU.

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References

[1]Robert C. Trevino, Joseph J. Kosmo, Amy Ross, and Nathalie A. Cabrol, "First Astronaut-Rover Interaction Field Test" SAE 2000-01-2482, *30th International Conference on Environmental Systems*, July 2000.

[2]Barbara Romig, Joseph Kosmo, Amy Ross, Craig Bernard, Lindsay Aitchison, Dean Eppler, and Keith Splawn, "Desert Research and Technology Studies 2007 Report" SAE 2007-01-3131, *37th International Conference on Environmental Systems*, July 2007.

[3]Andrew F. J. Abercromby, Michael L. Gernhardt, and Harry Litacker, "Desert Research and Technology Studies (DRATS) 2008: Evaluation of Small Pressurized Rover and Unpressurized Rover Prototype Vehicles in a Lunar Analog Environment" NASA TP-2010-216136, November, 2010.

[4]Shane E. Jacobs, David L. Akin, and Jeffrey R. Braden, "System Overview and Operations of the MX-2 Neutral Buoyancy Space Suit Analogue" SAE 2006-01-2287, *36th International Conference on Environmental Systems*, July 2006.

[5]Massimiliano Di Capua, David Akin, Kevin Davis, and Justin Brannan, "Development and Testing of Advanced Pressure Suit Technologies and Analogues for Earth-Based Simulations" *41st International Conference on Environmental Systems*, Portland, Oregon, July 2011

[6]David L. Akin, Mary L. Bowden, Srikanth Saripalli, and Kip Hodges, "Developing Technologies and Techniques for Robot-Augmented Human Surface Science" AIAA-2010-8001, *AIAA Space 2010 Conference and Exposition*, Anaheim, California, August 30-September 2, 2010

[7]Sandra G. Hart and Lowell E. Staveland, "Development of NASA TLX (Task Load Index): Results of Empirical and Theoretical Research" in P. A. Hancock and N. Meshkati, eds., *Human Mental Workload* pp. 239-250, North Holland Press, Amsterdam, 1988