EXPLORATION AND SAMPLE-RETURN MISSIONS WITH A WALKING ROBOT

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ABSTRACT

In order to truly explore far away planets with robots we need systems capable of going to hard to reach places and interact with the environment while beeing as autonomous as possible. The SpaceBot Camp was a challenge designed to highlight potential solutions for this problem on earth and foster development in this area. Team LAUROPE participated with the bio inspired hexapod LAURON V, specially outfitted to perform the difficult tasks of an exploration and sample-return mission. In this paper we highlight the changes made to the system for the SpaceBot Camp (in regard to the SpaceBot Cup 2013) with a special emphasis on issues arising for walking robots and schare our experience during the event.

Key words: Lauron, Space, Exploration, SpaceBot Camp, Autonomy, Mobile Manipulation, Competition, PlexNav, Control Architecture,Behaviour Based, Mission Control, Walking Robot, Hexapod.

1. INTRODUCTION

Exploration of distant planets requires some form of physical presence. We need to gather samples, explore hard to observe areas and interact with the environment to form a true understanding of it. Especially with far away planets, mobile robots are the perfect technology for this task as they can be deployed relatively easy and can execute long term missions even in hazardous environments as the two extremely successful Mars Exploration Rover (MER) spirit and opportunity[1] have proven.

With advances in robotics and space exploration, the requirements for the systems have grown significantly. While previously it was sufficient to move above the surface of a planet and take pictures or measurements, recently interaction with the environment and traversal of difficult areas has become a greater focus of robotic missions. The Mars Science Laboratory (MSL) is in fact more a laboratory on wheels than a pure exploration rover[2], combining newest robotic technology with proven rover methods. To identify novel concepts in these areas and improve the existing rover technology, challenges using some aspects of an analog mission have become an important tool. The NASA Sample Return Robot Challenge[3] for example requires complex, yet robust robots with a high degree of autonomy and a wide range of capabilities to overcome the difficult tasks and acts as catalyst to identify new potential for actual exploration missions. In 2013, the SpaceBot Cup (SBC13)[4], an exploration and sample-return mission challenge, was performed in Germany for the first time. Special focus of the SBC is a high degree of autonomy of the systems as well as the capability to safely traverse a difficult environment. The challenge inspired promising concepts such as the mechanically simple, but mission wise very effective robotic team Phobos and Deimos[5] or on the other hand the extremely sophisticated mechanical design of the Artemis rover[6].

In 2015 the SpaceBot Camp (SBC15)[7] continued this challenge scenario. The FZI participated as team LAUROPE with the six legged walking robot LAURON V [8] (see fig. 1). During preparation for the SBC13 many of its high level skills and the overall control framework PLEXNAV [9] were developed, greatly increasing the autonomy of the system.

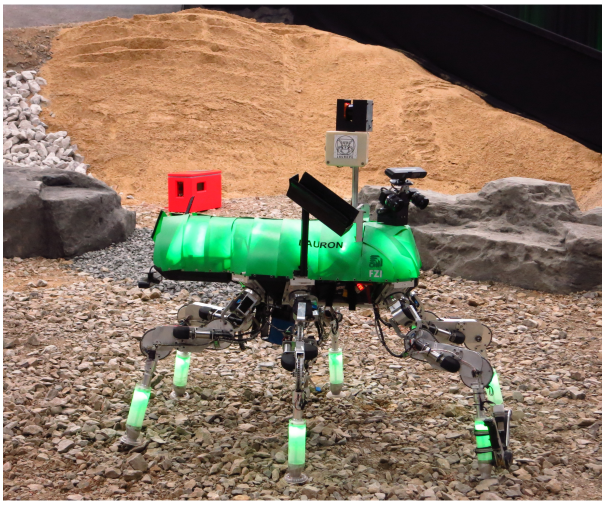

Figure 1. Bio-inspired walking robot LAURON V exploring a simulated crater

While in [9] the focus was set to explain the overall system architecture and developed high level skills, the focus of this paper is to present the work done in the context of enabling autonomous exploration with a bio inspired walking robot LAURON V. The paper is structured as follows: In Chapter 2 an introduction to the tasks of the SpaceBot Camp and our system LAURON is given. Chapter 3 then illustrates specific developments for the SBC with a focus on walking robot issues before chapter 4 concludes by discussing the performance during the SBC.

2. MISSION OVERVIEW

Exploration and sample return missions with robots are an extremely challenging task. The robot has to be capable to perceive, map and navigate a completely (or largely) unknown environment, locate, classify and manipulate objects while planning its mission and react to unforeseen obstacles and events. Such missions require both, a robust and versatile mechanical design capable of traversing such an environment as well as a complex software system to handle the various tasks. The SpaceBot Cup was initiated by the German Aerospace Center (DLR) in 2013 to identify novel solutions for this mission scenario with special emphasis on the autonomy of the systems. In 2015 the second instalment of the challenge, the SpaceBot Camp 2015 was held.

2.1. The SpaceBot Camp 2015

Figure 2. The simulated crater of the SBC15 consists of gravel, various types of sand and large rocks intended as obstacles. The red spot is fine gravel which is to be collected as sample

The SBC is an exploration and sample return mission set inside a lunar crater environment. The 18x13 m scenario (split in two fields) of the SBC was build up from various materials such as sand, very fine sand, gravel and large rocks intended obstacles (see fig. 2) reaching about 2 m at the highest point and presenting slopes of up to 35 °.

Initially, only a very rough height map of the environment is known to the robot making exploration, mapping and navigation an essential task for every robot. Figure 3 shows the height map created by LAURON during its run. Inside the crater two objects have to be located and retrieved: a yellow battery pack and a blue sample container. Both objects have to be brought to a third object, a red colored scale, where the sample should be placed on top and the battery has to be inserted from the side before an elastic switch has to be flipped. The rules and overall tasks are therefore the same as in the SBC13 [4, 9].

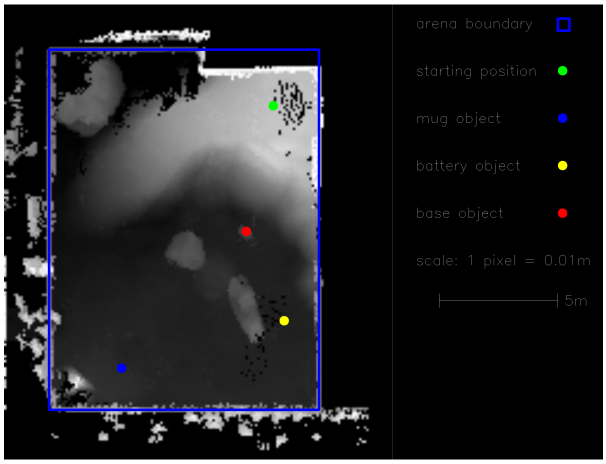

Figure 3. Refined height map created by LAURON during its run with automatically inserted object positions. Height ranges von 2 m (white) to 0 m (black)

All tasks have to be completed within one hour while the ground team can only monitor the progress of the robot via an unreliable network link with added artificial latency increasing the demand for autonomy of the robots.

One of the most notable difference to the 2013 challenge is the environment, which forces all participants to traverse a very steep slope, making mobility of the robot a key aspect to perform well. Among many minor changes, the most notable ones where the changed organisation of the event, giving teams more time to prepare on the actual course itself as well as a non public qualification round where subtasks had to be performed on a smaller environment (10x10 m). The qualification tasks however where not reduced in complexity compared to the final challenges, resulting in only 3 teams reaching the minimal threshold which led to the re-branding of the SpaceBot Cup to SpaceBot Camp, essentially dropping the challenge character and allowing teams to disable rules to give an optimal performance of their systems strengths. Team LAUROPE opted for the target object to be located within the crater rather than on the top of it and to permanently allow an uplink to the robot instead of just relying on two checkpoints. Other restrictions however, such as the added latency or port restrictions stayed in place

2.2. LAURON V and LANDER

The used System, LAURON V (fig. 1,4), is a six legged, bio-inspired walking robot modelled after the stick insect. It is especially versatile in rough unknown terrain where its 4 DoF legs provide the required mobility to easily traverse various obstacles but it can also use its two front legs as manipulators, removing the need for an additional robotic arm as payload. Outfitted with a custom made gripper [10], LAURON is capable of lifting objects of around 2 kg. More details on LAURON itself can be found in [8, 11]

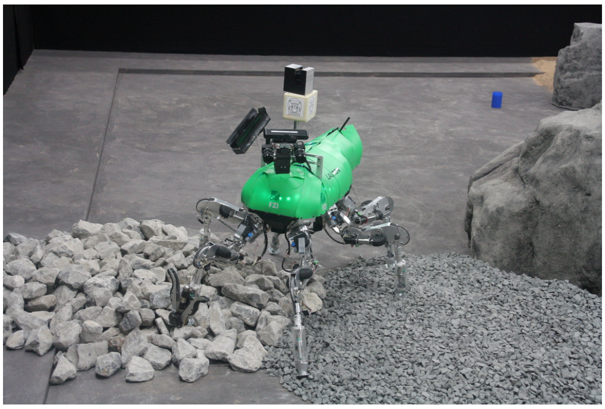

Figure 4. LAURON is able to traverse very challenging terrain without to many problems. His reactive behaviours can cope with lose terrain and leg slippage while inclination and height behaviors keep the body stable at all times

A behaviour based low level control is able to adjust the body posture and leg positions as well as walking behaviour to the environment, giving LAURON very good mobility options such as traversing slopes of up to 25 degrees inclination without any external sensor knowledge. For the SBC13, LAURON was outfitted with the gripper and compartments to store and retrieve the two objects as well as a rotating laserscanner system KaRoLa[12] to map the environment. In 2015, the system additionally received several hardware upgrades to increase its performance and robustness The head was replaced with a 3D printed version, providing improved cable guidance while the main gearbox of the alpha gear, providing the forward movement, was completely restructured to use worm gears which can produce a much higher force with smaller backlash than the previous version. A secondary RDBG camera (xtion) was placed at the abdomen of the robot to provide optical flow information and a high precision fibre optic angle sensor was installed as absolute angle reference for localization. With the added sensors, an additional computer (Intel Nuc with i7 processor) dedicated to visual processing was installed in the front body.

As in the SBC13, a secondary system, the LANDER (see fig. 5), was usedas a base station providing wireless communication with LAURON and an extendible mast carrying a high resolution movable zoom camera.

Figure 5. Base station used as secondary robot system. The LANDER is holding power supply units for itself and LAURON, establishes communication with the base station via its PC and communicates with LAURON over a WLAN access point. The mast carries a high resolution zoom camera with pan/tilt unit and can be extended up to around 5 m

3. EXPLORATION WITH A WALKING ROBOT

The complex environment and unforeseen obstacles during an exploration mission require very flexible robots that can adapt to many situations. Steep slopes, loose gravel or large boulders can easily bring smaller rovers to their limit, ultimately restricting the areas they can explore.

We therefore strongly believe that a walking robot is the best choice for such missions and have used LAURON V in the SBC to highlight the abilities of walking robots. LAURON is controlled with a hybrid architecture called PLEXNAV which has already been presented in [9]. This time we want to focus more on the walking robot specific parts of the implementation. PLEXNAV consists of 3 layers:

- The **Robot Layer** deals with robot specific implementations, access to hardware components and conversion of measurements. In the case of LAURON this layer is made up mostly by the behavior based control system

- The **Skill Layer** provides the deliberate high level functions of the robot. These are, if possible hardware agnostic but also incorporate some of the walking robot specific strategies

- The **Mission Layer** is the planning and mission control layer where decisions are made based on available information. This layer is also responsible to accept tasks from the base station and communicate the current mission progress

3.1. Robot Layer

LAURON uses a behavior based control approach to govern its basic walking capabilities[11]. By implementing small encapsulated behaviors rather than an overall control system, LAURON is very capable in handling unforeseen events as not every situation has to be encoded individually. This flexibility is a large advantage for difficult terrain. For the SpaceBot Camp LAURONs behaviors where extended to cope with the especially difficult terrain, most importantly to safely walk up and down slopes.

The inclino behavior is used to **manage the orientation of the body**. Usually the behaviors modifies the leg height as to always align the body orthogonal to the gravitation vector.

When walking up slopes however the legs further down the slope quickly reach their kinematic limit. Likewise, the legs opposite are very close to the body leaving little room to lift them up. If the body is kept parallel to the inclination the movement range is maximized, but the robot is easily prone to slippage. To solve this, measurements from the IMU are fused with a plane estimation of all footpoints, allowing the robot to align its orientation exactly in between the horizontal position and the slopes angle whereby the usable movement range of each leg is increased while keeping stability high. The same slope estimation is used to provide an offset to the body position behavior which shifts the center of mass up the inclination regardless of walking direction.

While these changes are very little, compared to other behaviors, the results on stability are significant as a constrained movement range for the legs will often result in improper foot placement which can lead to catastrophic failures.

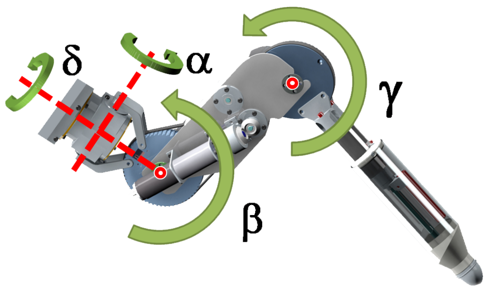

Figure 6. Kinematic of LAURONs legs

One of the most important task for a walking robot in such an environment is **maintaining a stable ground contact and body height**. The height behavior always tries to keep the body at the defined height from ground, pulling legs up if they are to far stretched and pushing them down if the height needs to be corrected. By doing so the body is automatically lifted if the front legs are stepping on an obstacle making sure that the ground clearance is kept. The ground contact reflexes push the legs towards the ground if the contact was lost, ensuring that the legs are further extended when the ground is lower than expected. This is the case when walking from a plane onto a downwards slope or onto very loose soil. In case the step is very large, the feet might not reach the ground before being extended to their maximum length. This can lead to the robot stalling in a deadlock or perform unsafe gait transitions.

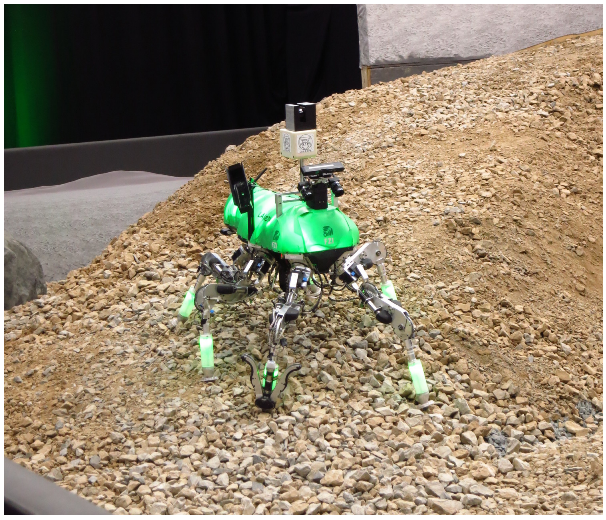

Figure 7. Multiple behaviors ensure a stable locomotion over difficult terrain, primarily steep slopes. If the legs can not reach the ground the body height is lowered, the center of mass is always shifted up the slope

We counteracted this problem with 2 behaviors. The height behavior was connected to the ground contact behavior to monitor if any leg is missing ground contact for a longer period. If so, the overall body height is lowered until contact can be established again. Additionally, the ground contact sensors were completely reworked to only rely on the measured motor currents. Previously potentiometers where fused with the currents which, while more accurate, could only detect ground contacts when standing directly on the foot which resulted in problems when walking in sand or with very wide stance. Both, the beta and gamma motor (see fig. 6), responsible for lifting the leg are used to detect a ground contact, which lead to the effect that basically any part of the leg can account for a ground contact as long as sufficient force can be applied to it. In fact, LAURON can detect that a leg is reaching the ground, even when the gamma segment is not working at all effectively walking on its knees. Both effects combined lead to the behaviour that LAURON might crawl at some kinematically difficult points, but can overcome steps of about 40 cm height without tipping over.

During the SBC, lauron stepped on one of the

Figure 8. By using all currents of the leg as potential foot sensor even contacts like this can be used as long as sufficient weight can be put on it. In this case the foot is only touching the boulder with its guard plate which unusually prevents sinking in loose soil

stones which where supposedly insurmountable obstacles. LAURON was walking very close to it and pierced the outher hull with the guard piece on the legs that prevent sinking. With this however he managed to get a reliable foothold almost climbing the rock (fig. 8). Shortly after this, an axle had an unrelated failure, leaving a gamma segment without actuation. While the then attempted walk was less than optimal, LAURON managed to get himself up multiple times, showing the robustness of the system even in case of a severe hardware failure.

3.2. Skill Layer

While the behaviour based system provides LAURON with the ability to cope with local problems, i.e. loose soil or unforeseen obstacles, it would be impossible to perform complex missions without high level skills. We have build upon the skills described in [9] and extended them or updated them where needed.

Localization in unstructured environment is a problem for all types of robots, but is even more difficult with walking robots. Global localisation is provided by laserscans with the KaRoLa sensor which produces a detailed 3D pointcloud of the environment[13]. As scans have to be taken when standing still and are fused via ICP the robot has to rely on relative localisation in between. Odometry information from the legs has the problem of slippage and play, leading to rather inaccurate solutions which need to be fused with other information. Integration of the internal IMU values produces similar or worse results. We therefore used an RGBD sensor to compute optical flow odometry. Additionally a high precision fibre optic angle sensor was used as absolute angle reference, greatly improving the odemetry information.

A main challenge when using optical flow with a walking robot are sudden ego movements. While optical flow handles smooth motions very well even when performing fast movements, sudden accelerations are difficult to track frame to frame and result in wrong measurements. However, such motions occur during every step of the robot, as each impact of the feet produces vibrations. Various countermeasures where evaluated with little or no effect. Mechanical dampening of the sensor produced only minor improvement as the dampening still has to be stiff enough to register small movements. Additionally, the mechanical effort required for a dampened sensor connection was much to high. Another approach was to track the movement of the legs and modify the covariance matrix of the sensed odometry every time the ground contact was established. While promising at first, the overall results were minor, as the vibrations introduced by the movement of the legs were enough to disturb the measurement significantly. The solution to this problem was an additional xtion which was mounted on the abdomen of the robot. Vibrations need to travel a long way through the main structure before being noticeable at this point. Furthermore, the previous position on the head was much more susceptible to motion due to quick accelerations. The mass of the sensors would pull the PTU belt drive enough to introduce wrong measurements.

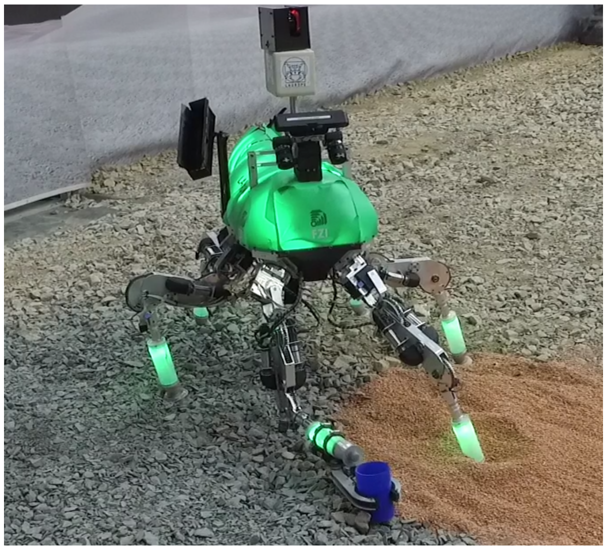

Figure 9. Lauron grasps the sample container filled with soil. The body is kept level even as one leg is deep inside the loose soil. The whole body is used to move into the optimal grasping position

Mobile Manipulation of the target objects was another challenging task for a walking robot. LAURON uses one of its front legs as arm for the manipulation by rotating the alpha-joint about 90 degree, putting it into an arm like configuration (see fig. 9). With 4DoF the legs are very versatile for walking, but underactuated when grasping resulting in very few spots where grasps are possible. This was compensated by implementing a full body inverse kinematic solver. When calculating a grasping solution, the position is first compensated by using the base as 6D positioning platform before actually calculating the inverse solution for the Arm. Still, the success of a grasp relies heavily on the initial position of LAURON as especially rotation of the body around the z axis introduces large forces into the legs. Inaccurate localization of the object, especially regarding the height additionally introduced errors when grasping.

To reliably grasp the objects we used several strategies in the following steps:

- To pick up objects, a goal point is generated in between the object and LAURONs current position at a fixed offset. This goal is used in the path planner to move towards this goal.
- Once the location has been reached, a fine localization of the object is performed by moving the PTU towards it before using a shape based model fitting approach.
- LAURON is then moving towards the object with a visual servoing approach. The goal position is estimated based on pre calculated optimal grasping positions relative to the goal object. During this step no planning or obstacle avoidance is used
- Once at grasping position the body is levelled, all behaviors are deactivated as removing one leg from the ground would otherwise lead to severe reactions
- The arm is moved into its grasping position with a fixed trajectory before the TCP is moved to the detected object position with an object specific grasp
- The gripper is closed and a fixed trajectory is used to store the object and return the leg to walking condition
- Finally, ground contact is re-established and the behaviours are activated again

A main problem with grasping the object reliable was a bad height estimate, while the position was met almost every time, the gripper would often close above the object or drive into the ground. This was mainly attributed to calibration drift of the xtion which could not be compensated adequately with calibration itself. We instead used the legs to estimate a plane around the robot and grasped the object as if it was standing on this plane if the height estimate of the sensor and the plane did not differ to much which lead to a very good grasping performance even when standing on difficult terrain.

3.3. Mission Layer

One of the pitfalls in the SBC13 was the use of a monolithic state machine for the overall mission control. While the state machine itself was designed to handle various situations, it was simply to complex to be adequately debugged and tested during development, leading to the ultimate failure that LAURON would not start at all. As already stated in [9], this structure was split up into a more flexible capability execution cycle where capabilities are executed individually. A simple state machine keeps track of the operation flow and enables the user to control the execution state by starting and aborting the capabilities as well as publishing the status of the execution. After each capability has been executed a second entity, the decision maker, is asked for the next capability to execute. The decision maker was implemented as simple node that keeps a fifo list of tasks and monitors relevant mission data such as the detection of an object or the status of the robot itself. If an object is seen which has not yet been collected, a new task to explore it can be added by the decision maker. This approach allows easy replacement of the overall strategies, without impacting the execution of the capabilities.

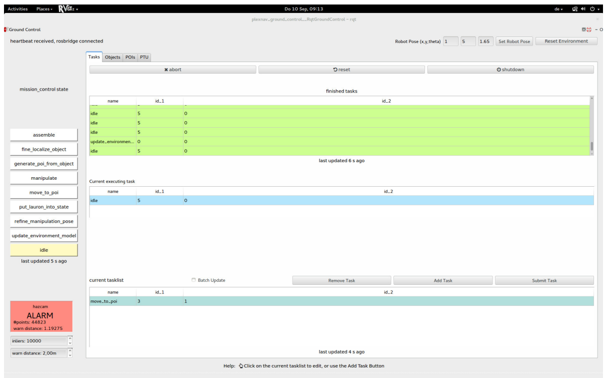

Figure 10. Ground station user interface of LAUROPE. The user can prepare what actions to take by selecting from a list of capabilitites (left), parameterize and queue them (lower box). Previous capabilities (top) and currently executed ones (middle) are shown in addition to sensor information such as the hazcam ("ALARM" window) which monitors obstacles in front of LAURON. Various tabs allow to inspect and interact currently known objects, point of interests and specialized functions like moving the PTU of LAURON

Figure 11 shows the interface used to trigger the execution of the capabilities. The operator can always see what capabilities have been or are currently executed and prepare a list to be sent to the robot. The available skills are listed on the left and can further be parameterized once the are inserted into the task list. The whole system is geared towards the checkpoint mode of the SBC, allowing the user to prepare complex chains of commands at the ground station before sending them as bulk commands to the robot once the uplink is available. The "ALARM" window notifies the operator if a large object is in front of the robot (detected by the xtion). Other tabs show the list of POIs, the currently tracked objects or allow manual selection of various functions such as the to set the PTU orientation, which is helpful when performing difficult manipulation tasks. Combined with a 3D environment view, camera images and direct gamepad control of the robot (if the uplink is available) this interface allows the operator to control all aspects of both robot systems, the LANDER (extend the mast, set the angle) and LAURON.

4. PERFORMANCE AND CONCLUSION

The SBC15 consisted of two parts, the qualification and the main event. In the qualification, a reduced environment was given where in 10 minute time slots the robots had to show how they could map the environment to construct a detailed height map, locate objects, pick them up and traverse challenging terrain.

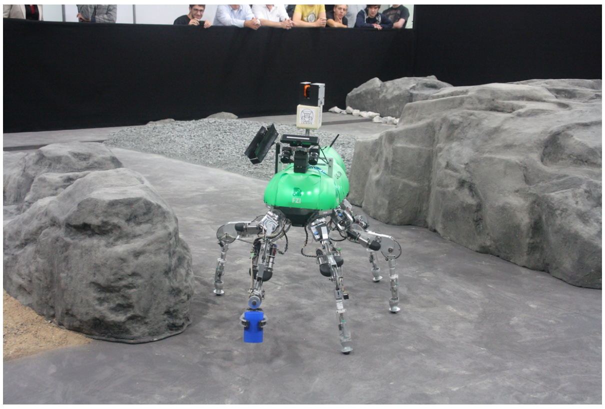

Figure 11. LAURON successfully grasping and storing the sample container at the qualifying. The walls are covered in black molton fabric

Team LAUROPE could unfortunately not qualify at this point. Main issue was the environment in which black molton fabric would not reflect any laser light at all while at the same time people moved directly behind the barrier, changing the environment for every scan. Because of this and the under-performing odometry due to vibrations, localization did not work properly, restricting us to switch to manual control of LAURON with a remote gamepad. At this point, the decision to bring the LANDER proved to be very beneficial as the high vantage point helped to identify difficult obstacles making a remote control possible, even with latency of 2-10 seconds (most latency was actually produced by our wireless connection). The connection system developed during SBC13 was updated to allow better reconnection which proved to be reliable, allowing the team to reach the target object. Grasping then proved difficult at first as the height of the object was not detected properly leading to grasps high in the air and because the inverse kinematics could not find suitable solutions as the positioning was not good enough.

We addressed both of these issues by the aforementioned solutions: better estimating the height and implementing the visual servoing mode for better positioning. The localization issues could be solved with the added xtion which provided much better odometry data, which in turn gave a much better estimate for the laserscan matching ICP step leading to a very good mapping result during the actual run (see fig.12).

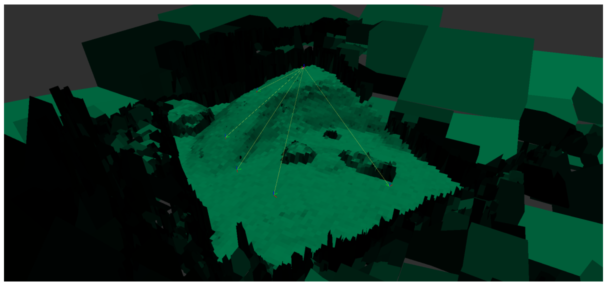

Figure 12. PLEXMAP build by LAURON during the SBC15 representing the terrain seen in fig 2 and 3. It is used for planning and feedback to the operator. Scanning positions can be seen as TF frames in the map

Unfortunately, due to these problems and a severed cable in one of the legs, we could not qualify by the rules. As only 3 teams were able to qualify, the overall competition character of the event was lifted and the final event was used to highlight the strengths of the systems, without a jury to judge the performance.

In the actual run, LAUROPE performed very well. We opted to control LAURON manually during its descend into the crater as the path planner would consistently only find 1 solution which meant that any localization error over 5 cm would have lead to a catastrophic failure. With about 80 cm width, LAURON was fitting barely onto the ridge, breaking of pieces of it if the optimal path was left which is exactly what happened during the run (see fig 13. The behavior based control was able to stabilize the situation quickly by leveling the body as best as possible before activating an emergency halt due to the high activities of the behaviors. After a reset onto the ridge LAURON managed to traverse the ridge without further incident.

After this, only high level commands via the mission control were given which resulted in the second error of the run where the operator triggered the pickup of the sample container from very far away. The resulting grasping position was based on an outdated object localization which ultimately pushed the container over. After we reset the container (nothing else was touched) LAURON immediately grasped it (fig. 9) as well as the battery object without any problem even though one leg was buried deep inside the loose sample soil.

During the visual based approach of the battery object the improved ground contacts were able to travers one of the boulders, and at a subsequent hardware failure LAURON was even able to walk some steps on his gamma segment.

Unfortunately this did not allow us to reach the target object, ultimately ending the run at that point.

Overall, we could show that a bio inspired walking robot is quite able to perform the tasks required in an explo-

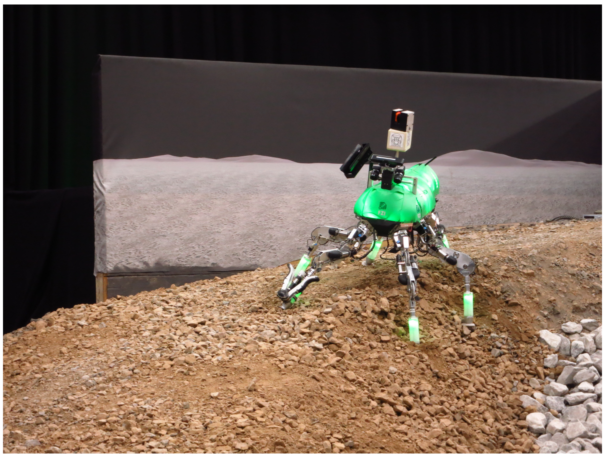

Figure 13. LAURON standing at the edge of the ridge leading into the crater. He got to close to the edge breaking it of completely. The behaviors however ensured that the body was kept stable and an emergency halt was triggered

ration and sample return mission. We could show that our robust behavior based system is able to compensate very rough terrain and even stop catastrophic failures by keeping the robot stable. The developed high level capabilities were updated and further enhanced to cope with the specialities of LAUROPE and walking robots in particular. The improved hardware set-up with additional sensors, the add on gripper and an xtion at the abdomen was working very well allowing us to compensate most of the problems during the qualifying. A crucial update was the shown mission control which enabled us to send and modify commands at any time making the debugging and testing much more flexible, ultimately resulting in a very robust system ready for further space exploration challenges.

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