Toward Space Exploration on Legs: ISS-to-Earth Teleoperation Experiments with a Quadruped Robot

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Abstract— **In uneven terrains of lunar and planetary surfaces, a teleoperated legged robot enables the exploration of areas that may be inaccessible to wheeled rovers. The on-going DLR-ESA Surface Avatar technology demonstration mission studies and validates technologies needed to realize the command of a heterogeneous robotic team with various command modalities. In the latest experiments, the crew on-board the International Space Station (ISS) is tasked to command a team of different robots with Scalable Autonomy, meaning they may choose to command the robots through direct control, shared control, or delegate tasks with Supervised Autonomy. One of the robots in the robotic team is DLR's small quadruped, Bert. Equipped with a robotic arm on its back, also serving as camera mount, Bert can observe its surroundings and pick up small objects. Due to its serial-elastic joints, the hardware is robust to impacts, which is critical for space deployment. Applying adaptive learning strategies, Bert's gaits can be (re)trained directly on hardware to adapt to different environment and gravity conditions. The quadruped as well as its back-mounted arm can be commanded through direct control by the astronauts via a joystick on-board the ISS. Additionally, simple preset task-level commands complement the user interface to ease the astronauts' workload. This paper presents the ISS experiments of the first legged robot telecommanded from space. Examining different aspects of Bert's telerobotic performance as well as the ISS crew feedback, we discuss the feasibility of teleoperated walking robots in space exploration.**

I. INTRODUCTION

As robotic technology is continuously advancing and increasingly capable of handling more complex tasks, robots are becoming viable, if not crucial, to explore and colonize space. They are planned to be part of upcoming space missions, such as Lunar Gateway [1] and Artemis [2], to support human astronauts. It is envisioned that the robots can semi-autonomously prepare infrastructure on celestial bodies, while the astronauts monitor the progress from a station in orbit and can remotely command the robots if needed or desired. To test this idea under real conditions, the METERON SUPVIS Justin project [3] has introduced a simulated extraterrestrial environment, where multiple astronauts successfully commanded the humanoid robot Rollin' Justin [4] on ground from the International Space Station (ISS) to carry out different tasks. The latest follow-up project Surface Avatar [5] is extending these investigations by setting more complex tasks and introducing a team of different robots that the astronaut can switch between.

Fig. 1. The quadrupedal robot Bert during the first (right) and second (left) ISS experiments.

One of the robots in the Surface Avatar project is the elastic quadruped, Bert (Fig. 1), developed by the German Aerospace Center (DLR) [6], [7]. In contrast to wheeled systems commonly used for space exploration, the addition of a legged robot allows to transverse rough terrain. Bert, in particular, is also small sized so that it can function as a scout to explore small openings like caves. The little quadruped was originally built to investigate energy-efficient locomotion by exploiting the potential of springs added as elastic elements [8]. These concepts of energy-efficiency are especially interesting for space exploration, where battery life and power budget [9] is an essential limitation in missions. Additionally, the springs make the system robust to impacts, which is also crucial in a space context as sudden winds can arise that tip over the robot. In the on-going Surface Avatar mission, a modified version of Bert was part of a robotic team, together with DLR's Rollin' Justin and the Interact Rover [10] from the European Space Agency (ESA). The mission involves multiple astronauts stationed on the ISS, tasked to carry out a series of protocols involving different robots. This paper presents the modifications and methods to prepare Bert for its mission protocol and reports quantitative

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findings on the task success and astronaut feedback.

II. METHODS

As part of the ISS experiment protocols in Surface Avatar, the astronauts were tasked to use the quadrupedal robot Bert to scout the environment for a target location, marked by loose colored screws. The astronaut should then command Bert to walk towards this target and position the robot to pick up the screws on the ground (Fig. 1). The current protocol only included Bert and not yet any interaction with Justin or the Interact Rover, aside from using their cameras for an external view on Bert. The hardware and software required for the Bert protocol are detailed in the following. It included the modification of the quadruped to mount an arm with a camera to screen the environment and interact with the screws. This necessitated the adjustment of Bert's learned locomotion patterns. Additionally, the camera images had to be processed to locate Bert in the simulated Mars environment. Due to very limited bandwidth, it was essential to carefully select which information would be streamed to the astronauts. Furthermore, the available commands for the astronauts needed to be intuitive and keep the mental workload low.

A. Quadruped Design and Modifications

The quadruped Bert with 8 degrees of freedom (DOF) was originally developed to investigate robotic design and control based on intrinsic mechanical system elasticities added through Series Elastic Actuators [6]. The main focus of this investigation had been on locomotion, such that prior to the ISS session Bert did not incorporate a robotic arm nor a camera. Both were added for the purpose of the here described mission, requiring to keep development effort low. Therefore, the arm mounted on Bert's back was based on the leg design of a follow-up version of the quadrupedal robot. The arm's base and the first link are 3D printed plastic parts, the last link consists of a small carbon fiber tube (Fig. 1). At the end of the tube, we mounted an electromagnet with a nominal magnetic holding force of 20 N. Size and shape of the objects to pick up in the session were chosen in accordance with the magnet capabilities. The arm is equipped with three rotary joints: a base joint for turning the arm left and right independently of the robot's base orientation followed by two joints in an elbow configuration. The latter two joints are kinematically decoupled through a belt drive so that motion of the second arm joint does not affect the angle of the third joint relative to the base. This feature is particularly helpful during direct teleoperation of the arm detailed in section II-D. Combining the arm joint motions, the tool center point (TCP) can be moved freely in 3D space, but does not allow to control its orientation.

Due to Bert's limited carrying capacity, the structure of the arm links was designed as lightweight as possible, reducing stiffness as a trade off. The servo motors of the arm are identical to the ones used in the robot's legs, but are not coupled to elastic elements [6]. The off-the-shelf brushless servo motors have custom electronics and communicate via EtherCAT. They are commanded in position control, where each servo of the arm is tuned individually. For navigation, a camera (Sec. II-C) is mounted on the last joint so that its view aligns with the direction of the TCP. A small laser pointer is mounted next to the camera directing its beam toward the TCP to support the astronauts in aiming the magnet. In total, the arm adds about 1 kg of weight to the robot's 4 kg body.

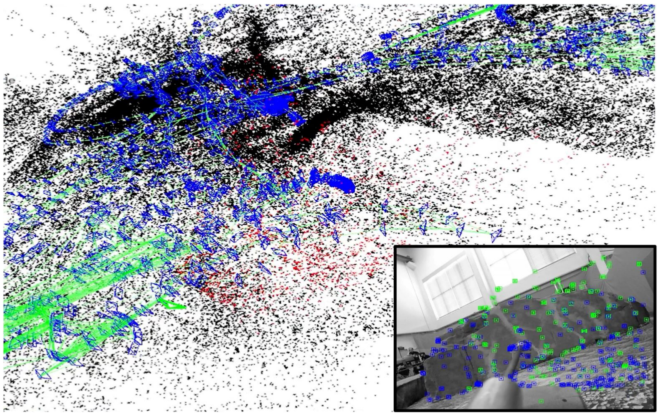

Fig. 2. Illustration of the feature-based SLAM approach to localize Bert in the global frame. As shown in the bottom right frame, 2D point features are extracted from the camera stream for visual tracking and combined with associated depth information to create a sparse spatial representation.

B. Locomotion Control

The robustness added through the elasticities in Bert make it possible to learn control strategies directly on the hardware [8], [11]. This is particularly useful for low-cost robots with limited sensing capabilities and unknown elasticities, where transferring results from simulation to real-world applications is challenging due to inaccurate estimates of hardware dynamics [12]. Instead, training Bert directly on hardware allowed us to discover various gaits, including those that seem impossible given the available kinematics and DOFs [8], [12]. Notably, this includes turning on the spot, a crucial motion for navigating in space missions. Although Bert lacks joints for leg abduction, this motion pattern can be achieved by exploiting the slip effects of the feet, which were discovered in previous learning trials [12].

In its current implementation for Surface Avatar, the weight of the quadruped Bert was heavily increased due to the back-mounted arm, adding 25% of the robot's body mass on its back. This altered the robot's dynamics and symmetry. As a result, the previously optimized learned parameters had to be adjusted to enable the robot to walk and turn again. Thanks to a learning strategy based on oscillators [8], [12], new gaits were found by training directly on the robot in less than 30 min, using only the on-board sensors and computer.

C. Camera and Spatial Perception

The robotic arm mounted on Bert's back was not only needed to pick up the screws, but additionally served as mount for the camera to record Bert's perspective of the environment. The integrated camera was an Intel RealSense D455 camera, providing RGB images along with depth

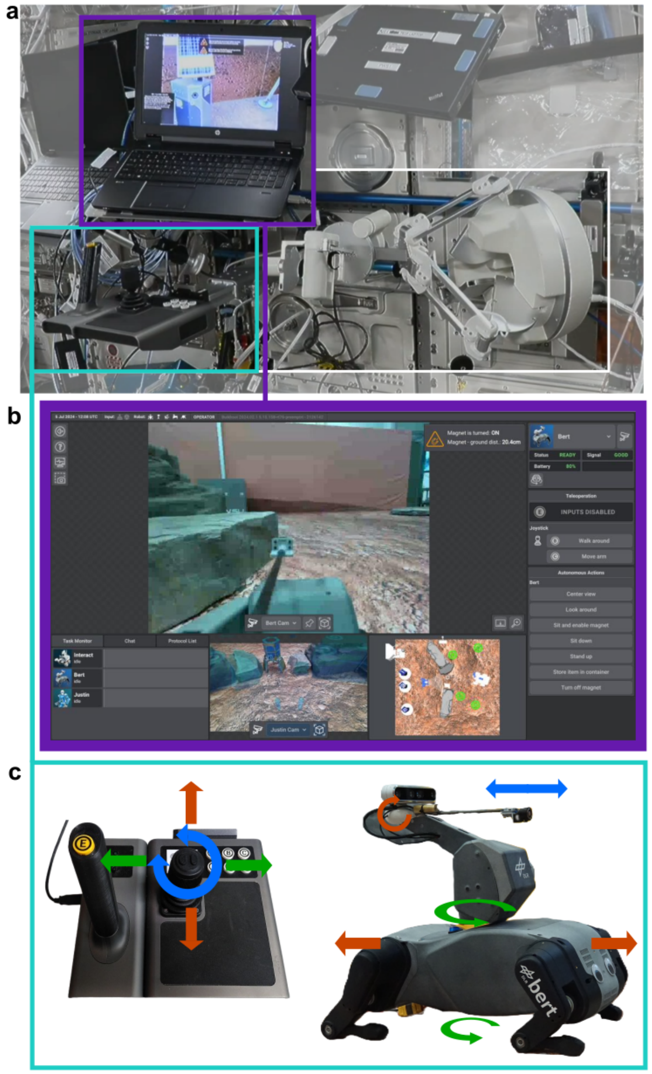

Fig. 3. The Robot Command Terminal (RCT) on-board the ISS and the command functions for Bert: (a) Overview of the RCT setup [5] including a Laptop computer with the Surface Avatar GUI (purple), a 3-DOF joystick (green), and a 7-DOF force-reflection input device (white, not yet utilized for Bert). (b) Close-up view of the GUI while commanding Bert. The user may use preset task commands in the task command panel on the right, or select the aforementioned joystick for direct control. (c) Mapping of the joystick motions to the robot motion and arm motion, respectively. The straight blue arrow denotes the zoom capability of the arm, which is realized through the decoupled kinematics of the joints.

estimation (Fig. 2). The camera information was used to observe the arm motion during the pick-up task as well as to locate Bert's position on the environment map presented to the astronaut. For the latter task, a vision-based Simultaneous Localization and Mapping (SLAM) approach was selected for estimating the robot's ego pose in the global frame. However, the processing power of Bert's on-board computers is not sufficient for delivering an online pose estimation. For this reason, the camera stream is wirelessly transmitted to a stationary computer for further processing. A frame rate of 5 Hz was selected, which provides an acceptable buffer against disturbances during the wireless connection. The localization and mapping framework is based on MROSLAM [13]. A particular feature of this approach is that it does not rely on predefined landmarks or artificial fiducials, e.g., AprilTags. Instead, a feature-based spatial representation of the environment, as illustrated Fig. 2, is constructed from visual and depth information, while the camera pose is estimated in parallel. This approach creates a more scalable environmental setup and allows the exploration of previously unknown areas. Bert's final body pose in the global frame is calculated using the inverse kinematics of the robotic arm.

To provide the operator with a video feed with acceptable quality and low latency, a camera stream is encoded from the RGB sensor. However, due to limited network bandwidth to the ISS, the video stream needed to be extensively compressed, which required a considerable amount of processing power. For this reason, the video encoding was carried out on the stationary computer, utilizing the already transmitted image sequences for the localization and mapping process.

D. *Astronaut Command*

The integration of Bert into a team of robots and the robot-agnostic user interface (UI) was achieved through knowledge driven teleoperation [3]. This approach combines a shared knowledge base with advanced teleoperation, enabling operators to manage robot teams more effectively. The system stores procedural and domain-specific knowledge, generating context-appropriate commands for robots with varying autonomy levels. It also allows operators to switch between direct control and higher-level task management, making it versatile for different missions. Robotic assets with limited processing resources, such as Bert, can still be part of the system by representing them as objects within the knowledge management framework. By publishing available command options to the system, these robots contribute to missions alongside more autonomous counterparts.

For the here presented Surface Avatar mission, a Robot Command Terminal (RCT) deployed on-board the ISS gives the astronauts a multi-modal UI to command our robotic team (Fig. 3). It was first introduced in the ESA-DLR Analog-1 misison [14], and includes a notebook with custom developed Graphical UI (GUI), a 3-DOF joystick, and a 7-DOF force reflection input device [5], [14]. The Scalable Autonomy teleoperation implemented on the RCT enables the user to operate multiple robots with different levels of immersion and task delegation. The setup uses ESA's software suite to establish an IP connection between the RCT on board the ISS and the robots in the Mars Simulator on Earth. It uses a satellite relay system which provides a data link with a bandwidth of 4 Mbit/s up/down and a communication delay of approximately 800 ms. More details can be found in [15].

For Bert, the astronaut on board the ISS could choose the joystick for direct control, as well as select task level commands with preset task trajectories for the arm and legs to reduce the astronauts' workload.

The GUI view for Bert presents two camera windows simultaneously such that the astronauts can select an additional stream of any camera of the available robots to gain an optimal overview of Bert's surroundings through different perspectives (Fig. 3b). A notification panel in the top-right corner of the GUI shown in Fig. 3b gives the astronauts feedback about the robots' status. For Bert, it shows the status of the electromagnet (on or off) as well as the estimated distance of the magnet to the ground calculated from forward kinematics. A negative distance value indicated that the ground was touched. To increase the operator's situational awareness, the robot was visible on the map showing the entire experiment area in bird's-eye view as shown in the bottom right corner of Fig. 3b. Additionally, the map gave the astronauts hints on where to go next by indicating possible pick-up locations of loose components with green target signs. On the right side of the GUI the astronaut can select if the joystick motion controls the robot's body, i.e., walking around, or only the motion of the back-mounted arm with the electromagnet on the tip. When commanding the robot, the astronaut could tilt the joystick forward/backward to start a trotting gait in the respective direction (Fig. 3c). The motion was stopped when the joystick was released. The velocity of the motion was predefined by the gait. Similarly, tilting the joystick left/right started an on-spot turning motion with fixed turning speed. Due to the limited 8-DOF kinematics of Bert simultaneous walking and turning is not possible. When controlling the arm, each DOF of the joystick is mapped to one DOF of the arm, allowing direct teleoperation through the astronauts. Tilting the joystick left/right turns the first (base) joint. Tilting forward/backward moves the third arm joint and therefore moves the camera up and down. Twisting the joystick handle clockwise or counterclockwise controls the second arm joint. Due to the decoupled kinematics (Sect. II-A) this acts as zoom motion, moving the TCP and camera in/out while preserving the viewing angle of the camera relative to the ground (Fig. 3c, blue).

In addition to the direct control modes, we implemented a list of preset motions, which were fixed position commands to relieve some mental work load off the astronauts. These commands are autonomously executed via button click available on the right side of the GUI (Fig. 3b). They include `Look around` to adjust the camera view with two sliders for vertical and horizontal motion, `Center view` to move the camera view to an initial pose, `Sit down` and `Stand up` to command Bert to either go into a position with full ground contact of the body or stand up into walking position, respectively. The commands `Magnet ON` and `Magnet OFF` toggle the state of the magnet and `Stow item in container` autonomously moves the TCP of the arm above a stowage container at Bert's back and releases the magnet. Due to the significant weight of the arm compared to the robot's weight, stable walking is only possible when the arm is centered. Therefore, whenever the astronaut selects walking control via the joystick, the arm automatically moves to a predefined position before allowing the astronaut to start moving. Similarly, turning on the magnet automatically seats Bert to have the robot in a stable position and to decrease the distance between arm and ground. This autonomous behavior was indicated to the astronauts by the operator at protocol start to prevent potential confusion.

III. RESULTS

The commissioning of Bert in the ISS teleoperation experiments has been carried out in two phases so far, with an additional one planned for a future session. In January 2024, Bert was first added to the robotic team of Surface Avatar, where the astronaut was tasked to walk around with Bert to find and describe different targets. This helped to validate the sufficiency of the sampled down frame rate of the Bert camera. The astronaut could intuitively switch between commanding Bert and the arm on its back, successfully locating all targets. Due to bandwidth and image processing power limitations, the video stream quality was low during locomotion. However, when statically standing, the low sample video stream was sufficient for the astronaut to give a detailed description of target features (Tab. I).

In the following ISS session in July 2024, more complex tasks were incorporated in the Bert protocol. In addition to walking, Bert had to pick up objects from the surface such as loose screws and bits. Bert was commanded in two sessions on consecutive days by two different astronauts, both carrying out the same protocol (Fig. 4). The protocol involving Bert was scheduled to last 25 min. Both astronauts could successfully identify the target locations, where the screws were set up. It showed that in addition to Bert's camera, they heavily relied on the second camera view showing the perspective from either the Interact Rover, Justin or a watchtower capturing the complete simulated environment. In the questionnaire given to the astronauts after the end of the session, both astronauts stressed that this feature was extremely useful during the Bert protocol giving it a rating of 6/7 on the Lickert-scale. The astronauts also reported that they could intuitively switch the joystick control from commanding the robotic arm to moving Bert forward. This was supported by the preset motions that automatically positioned the arm for walking with Bert, which relieved the astronauts from mental workload to remember changing the arm position before moving the robot.

Both astronauts successfully commanded Bert to walk to the the target location to pick up the screws. Finding the target location and walking towards it took the astronauts around 10 min. The remaining 15 min were completely

Fig. 4. Astronauts Tracy C. Dyson (left) and Jeanette Epps (right) commanding Bert with the RCT in the Surface Avatar ISS experiments.

TABLE I

TASK SUCCESS OF THE BERT PROTOCOLS IN SURFACE AVATAR ISS-TO-EARTH TELEROBOTION EXPERIMENTS

ISS Incr.	Date (M/Y)	Crew	Success/ Fail	Protocol (Task)
70	1/2024	1 ESA astronaut	Success	Environment traverse with walking
			Success	Target localization with arm-mounted camera
			Success	Identification and description of target details
71	7/2024	2 NASA astronauts	Success	Environment traverse with walking
			Success	Target localization with arm-mounted camera
			Success	Identification and pick-up of loose components with stowage
			Success	Transition between arm and robot using presets and direct control

used to achieve the task of picking up a screw. The main challenges during this task were the limited bandwidth, which necessitated a low frame rate of the Bert camera, and signal delays, which caused a lag for the arm commands. Additionally, the astronauts were only provided with a 2D image, which made depth perception difficult. The astronauts had to rely on the indicated distance of the arm's end tip to the ground to validate contact with the screw as no force feedback was provided. Although the laser pointer helped to initially position the robotic arm, it appeared to point slightly offset to where the electromagnet reached when fully extended. While the astronaut of the first session seemed to find the joystick mapping to the arm motions intuitive, we could observe occasional direction mix-ups for the second astronaut. Nevertheless, eventually both astronauts successfully picked up a screw with the robotic arm. Once achieving the pick-up, they both chose the offered preset motion that allowed Bert to automatically store the screws in the bin attached to its back (Tab. I). Both astronauts expressed verbal joy and excitement when achieving the task. The feedback of the robotic mission was overall very positive and all astronauts communicated that the system and concept is easy to understand and learn.

IV. DISCUSSION

All astronauts successfully completed the given tasks with Bert. In the January experiment, the astronaut commanded Bert to walk around and move the arm to observe and survey the surroundings. In the latest Surface Avatar mission in July, the two tested astronauts additionally completed more complex tasks of the Bert protocol successfully. They located the target area with the screws with Bert's back-mounted camera and additional camera views. Despite challenging remote control due to time delays and limited bandwidth, both astronauts could successfully pick up a screw with the robotic arm and store it in the bin attached to the robot. The transition from using the joystick for the arm control to the robot walking appeared seamless for all astronauts.

The successful completion of the pick-up task indicates that the sampled down frame rate of the video stream was sufficient to interact with the robotic arm. Both astronauts reported that the video quality did not interfere or distract with the performance of the assigned tasks (1/7 on the Lickert scale). The astronaut performance in the January experiment supported this reporting as the video quality was good enough to identify details of targets when the camera was static. However, all astronauts also reported that it was extremely useful to switch to camera views of other locations, especially during the walking of Bert, where the excessive movement of the camera on Bert's back was causing a blurred image. Thus, the down sampling of Bert's camera stream appears acceptable for static observations and slow tasks as long as other cameras are available for visual support and to navigate of the robot.

More than the video quality, the pick-up task seemed to be challenged by varying delays in the command feedback due to processing of the camera stream and a lack of understanding how far away from the ground the arm's TCP was. In addition to the communication delay of 800 ms, the camera stream added delays of up to two seconds until the video stabilized after motion. To improve this in future experiments, force feedback could extend the arm control to validate contact with an object. Additionally, picking up screws was complicated by the limited dexterity of the arm. For successful pick-up, the magnet needed to be aligned almost orthogonal to the screw, which required the astronaut to approach straight from the top. Deviating approach angles resulted in failure to pick up most times.

The preset commands showed to be very useful as they released mental workload from the astronauts. The fact that the astronauts did not have to reposition the arm in a walking configuration when switching to command the robot made the transition seamless. Also, the fact that Bert automatically went to a laying position to increase its body stability and turned on the electromagnet when the astronaut attempted to pick up the screws aided the task transitions. However, it did become clear by the astronauts' verbal feedback that it is not trivial how a task command is named in the GUI, as it can confuse the astronauts if preset commands are mentioned in the protocol description but do not need to be carried out manually. Although useful, the concept of the preset commands is contrasting the common approach of teleoperation setups, where the robot is usually aware of it surroundings and plans a motion accordingly. If a rigid robot runs into a collision it can be detrimental for the hardware and should be avoided at all costs. However, Bert's hardware is protected from impacts through the springs decoupling the motor from the link. Thus, if a preset command caused a collision, it would merely be a failed attempt after which the robot can be rearranged to repeat the preset attempt.

It needs to be mentioned that with the arm being 25% of the robot's weight, Bert was heavily overloaded, which manifested in slow and strained motion patterns. Nevertheless, it was remarkable how quickly the robot's motion patterns could be adjusted with the online-learning approach on hardware. This provides a useful feature that cannot only be used when modifying hardware but is equally useful when employing the robot on celestial bodies, where the gravity does not match the one on Earth, on which the robot control was tuned. As changed gravity has a similar effect to adding or lifting load to the robot's mass, the hardware learning approach could also help to update pre-trained motions in space. The fact that Bert was overloaded during the task was due to the original design focusing on energy-efficient locomotion only, not accounting for additional weight to be added. However, in the development of Bert, tools were established that allow to shape the design of elastic robots such that they embody desired motions [16]. Using these tools, a new design for Bert could be imagined that includes an arm in the design process. For the current version of Bert, it could be envisioned to remove the arm, instead employing Bert more heavily as a scouting robot to exploit its advantages of hardware robustness and potential for energy-efficiency due to the system elasticities. Although the simulated Mars environment did not feature a dusty terrain, as a real celestial body, [7] tested a similar version of Bert in two different dust-rich environments over a time span of multiple months. For these experiments all openings and legs had been covered, which successfully prevented hardware degradation from dust, keeping the robot fully operational.

V. CONCLUSIONS

Legged robots expand the reach to different terrains in space. Paired with the multi-modal RCT console, they provide powerful telepresence systems to explore and survey extraterrestrial surfaces. As the first quadruped robot commanded from space with Scalable Autonomy, Bert has shown the feasibility of legged locomotion in space exploration. The Surface Avatar ISS sessions demonstrate the control of legged robots can be intuitive and the robot's integrated elasticities appear as promising feature for improved energy-efficiency and robustness, both key concerns in space. Here, we presented the newest results from the very recent ISS experiment, such that the we only presented preliminary results, observations, and astronaut feedback. Further data will be analyzed and collected in the follow-up ISS sessions next year to derive more comprehensive and quantitative insights. Going forward, our future work will address open challenges for quadruped deployment in space. This includes further development of robust and energy-efficient locomotion, improved image processing and streaming, as well as better integration with other robotic assets. Combining these will provide the user with another powerful telepresence tool as a part of the (tele)robotic team on extraterrestrial surfaces.

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