

Skid-steering Telenavigation with Extended Predictive Polygon Method

Harsimran Singh¹ Michael Panzirsch¹ Mallikarjuna Vayugundla¹ Yunis Scheeler¹
Martin J. Schuster¹ Riccardo Giubilato¹ Ribin Balachandran¹ Jörg Langwald¹ Harald Wagner¹
Thomas Hulin¹ Armin Wedler¹

Institute of Robotics and Mechatronics¹
German Aerospace Center (DLR)
Muenchener Str. 20, 82234 Wessling, Germany
firstname.lastname@dlr.de

Abstract—The future moon missions will support extensive exploration activities, including remote operation between astronaut missions. The recent discovery of a lunar cave opens exciting possibilities for future exploration, as these natural formations could provide crucial protection for astronauts from the Moon's harsh surface conditions and harmful solar radiation. Despite significant advances in autonomous driving systems, their application in lunar exploration is constrained by uncertainties in environmental reconstruction and incomplete scene analysis due to occlusions. As a result, teleoperation emerges as a vital fallback solution for such missions. However, one of the primary challenges in bilateral teleoperation is the communication delays, which can destabilize and impair its performance. To address this, the current work extends the position-force predictive polygon method to skid-steering wheeled mobile robots (WMRs). By incorporating an intuitive haptic interface and a passive position-scaling mechanism, the system allows the human operator to adjust their commanded curvature input, ensuring it better matches the turning radius of skid-steering WMR. Experimental validation demonstrating the passivity of the proposed framework, along with discussion on how position scaling affects the system's overall performance is presented.

1. INTRODUCTION

Future wheeled mobile robots (WMRs) developed for lunar and Martian exploration will incorporate advanced autonomous driving systems and include versatile features such as a cargo bed for carrying robotic arms. These capabilities will be integral to a wide range of exploration activities, including sample collection, habitat construction, and remote operations during intervals between astronaut missions. The recent discovery of a lunar cave further enhances the prospects for human exploration, as such caves could provide natural shelters for astronauts from the harsh lunar surface and intense solar radiation. A WMR would play a pivotal role in exploring these caves, gathering scientific samples, and assisting in establishing long-term habitats.

Despite significant progress in autonomous driving technologies, their application in extraterrestrial environments is still challenged by uncertainties in environmental mapping and scene analysis, especially in areas with limited visibility due to occlusions. These uncertainties necessitate the use of large safety margins, limiting the autonomous system's ability to fully exploit its capabilities. As a result, teleoperation remains an essential fallback solution, enabling human operators to take control of the WMR from orbital

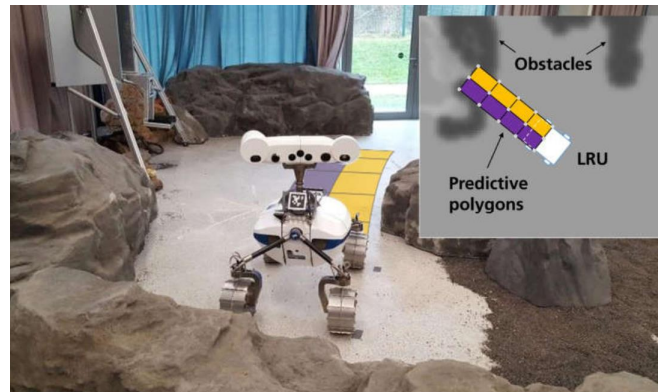


Figure 1. Predictive polygon method implemented on the light weight rover unit (LRU) with a car-like interface.

spacecraft, landers, or even Earth when complex or high-risk tasks require human judgment and expertise.

For remote bilateral teleoperation scenarios, precise position control is beneficial [1]. However, it is also important to shift the control focus from position tracking to enhanced force feedback [2]. In bilateral teleoperation, this is achieved by providing force feedback derived from sensor-measured interaction forces [3], computed forces from the impedance controller [4][5], or even fictitious forces which are generated from virtual environment (VE) models [6][7]. This feedback enriches the operator's immersion and control precision, improving the operator's situational awareness during challenging operations.

However, teleoperation over large distances introduces significant communication delays, which can destabilize and degrade the system's performance. Significant research has been directed toward addressing the challenges of communication delays in telenavigation. For instance, studies have focused on haptic interfaces [8], compensation for longitudinal slippage in wheeled mobile robots and the use of Time Domain Passivity Approach (TDPA) to address non-passivity induced by longitudinal slipping and lateral sliding [9]. Additionally, wave variables have been employed to stabilize two-channel tele-driving systems [10], and control methods based on Llewellyn's criterion and wave variables have been proposed to mitigate non-passivity due to slippage and constant communication delays [11]. Passivity-based adaptive scaled coordination control design was proposed for teleoperation

of car-like robots, incorporating communication delay and dynamic parametric uncertainties [12]. To further address latency issues, predictive models that integrate human driver commands, past video frames, and vehicle status have been proposed to provide real-time, latency-free driving scene predictions [13].

To address the challenge of bilateral teleoperation, we employed passivity, which serves as a useful tool for conducting energy-based analyses to evaluate system stability. We extended the TDPA, a method that has been successfully tested in various space telemanipulation experiments [14]. TDPA ensures system stability by dissipating excess energy through virtual dampers, allowing for safe and stable operation despite high and variable communication delays. Its modularity also makes it suitable for WMR telenavigation [15]. An interesting artifact of TDPA, position drift, which is often considered detrimental for telemanipulation can be exploited for modifying the intended trajectory of the WMR when combined with fictitious force feedback. This insight has led to further enhancements in TDPA for high-delay telemanipulation tasks [16].

This paper addresses the challenge of achieving stable and safe teleoperation of a remote skid-steering mobile robot under high and variable communication delays. One of the essential elements in achieving this is the creation of local maps, on the human operator side, of unknown environments. For this purpose, we adapt an existing on-board mapping and localization system for ground robots operating in unstructured environments, resulting in a local 2.5D virtual environment (VE) that is employed for teleoperation control and visualization [17]. To assist with collision avoidance from feedback forces, we employ the predictive polygon method [18]. This method considers a virtual curvature polygon placed in front of the WMR to generate fictitious forces based on the height values of obstacles that overlap with the polygons. These forces provide feedback to the human operator, helping to steer the robot away from potential collisions [19]. While initially designed for car-like WMRs, the predictive polygon method is extended in this work to accommodate skid-steering mechanism.

Despite the extent of research in teleoperation for car-like mobile robots, limited work has been done or only simulation results are presented for teleoperation of skid-steering mobile robots [20]. Skid-steering, which offers both high mobility and a large payload capacity with a simple mechanical structure, is especially advantageous for planetary exploration, where rough terrain and heavy cargo are common challenges [21]. It has been widely used in applications ranging from military operations to agricultural and exploratory missions. However, skid-steering is demanding regarding control on different grounds [21][22]. This poses specific challenge, particularly when the commanded curvature from the human operator differs from the actual turning radius of the WMR. This would further result in depreciated force feedback quality which could be ineffective in avoiding collision. To mitigate this, we introduce a position-scaling mechanism into the control loop, to adjust the commanded curvature to better align with the real movement of the WMR. We demonstrate, with experimental data, how this scaling can be designed without compromising the system's passivity [23], ensuring stable and accurate predictive polygon based telenavigation for skid-steering WMR.

The paper is structured as follows: The background is presented in Section 2. Section 3 introduces the proposed control approach. Experimental results are presented in Section 4 to validate the advantages of the proposed method, showcasing

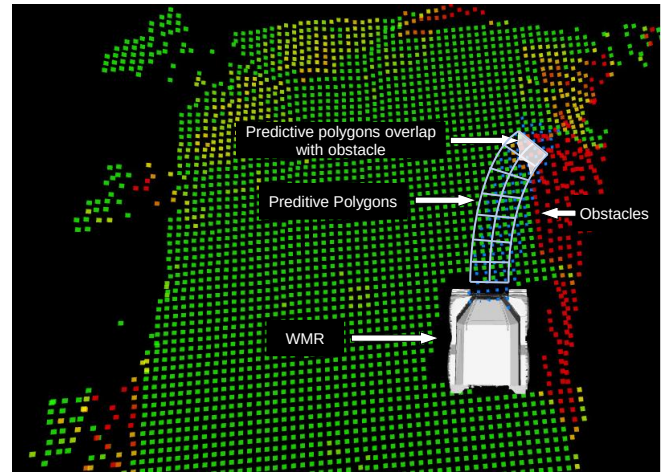


Figure 2. WMR as seen in the danger map. The predictive polygons (in blue) when overlap with the obstacles (in red), fictitious force is generated, which is cued to the human operator through the haptic device.

its effectiveness in maintaining intuitive, safe and stable teleoperation despite high communication delays. Finally, Section 5 concludes the work.

2. BACKGROUND

The extended model-mediated teleoperation framework for mobile robots explored the teleoperation of a rate-controlled WMR under high-latency communication conditions, by incorporating both local and remote force feedback [18]. The system employed a 2 degrees of freedom force-feedback joystick as the haptic interface to control the DLR lightweight rover unit (LRU). To manage the three horizontal degrees of freedom (DoFs) of the LRU, a car-like interface was preferred, offering curvature and longitudinal velocity commands. This design ensured smooth operation without rotational interruptions, which are typical in 2-DoF systems. However, curvature commands posed a challenge for generating intuitive fictitious force feedback using traditional potential fields, due to the continuous force reflection throughout the task. To address this, the virtual environment (VE) implemented a predictive method based on the curvature polygon. These polygons are used to assess the traversability of the terrain, as indicated by the LRU's pan/tilt stereo camera system, which acquires depth data and generates a local danger map. The polygons determine the fictitious forces applied to the haptic device, pushing it left or right depending on the obstacle overlap, see Fig. 2. The LRU creates this danger map relative to its horizontal plane, with additional feedback from the IMU's gravity vector to account for slope effects, enhancing the haptic feedback.

The control architecture integrates delayed feedback from the IMU with local model-based feedback to provide real-time force feedback to the operator [18]. To guarantee overall system stability, passivity observers (PO) and controllers (PC) are employed on both sides of the communication channel (CC). This ensures a passive CC and a passive VE, making the control loop robust to communication delays. Even when the operator is not actively moving the haptic device, power derived from the desired velocity and force feedback is transmitted to the LRU, ensuring continuous interaction.

A thorough user study was conducted which revealed key

insights into the effects of force feedback (FF) on telenavigation [19]. A consistent decrease in lateral force in the presence of FF across all subtasks indicates safer navigation, as FF induced subjects to adjust their trajectory to minimize overlap with obstacles. This feedback prevented unnecessary collisions by altering the user's input, and the positive impact of position drift. The position drift specifically occurs when the control polygon overlaps with obstacles, preventing the overlap from increasing, whereas without FF, users are more likely to steer directly into obstacles.

The study also found that average velocity tends to be lower when FF is present, suggesting that participants drove more cautiously. FF limits the ability to drive at higher speeds and enhances driver awareness and safety even in close proximity to obstacles. Interestingly, while FF reduced velocity, no significant difference in completion time was observed, indicating that users followed more efficient paths with FF, as they made fewer adjustments to their trajectory compared to when FF was absent. This suggests that FF helps users follow smoother, safer, and more direct paths. Overall, the study highlighted the tangible benefits of using force feedback in challenging physical environments, particularly when integrated with a stability controller, demonstrating safer and more efficient rover navigation even under significant communication delays.

Therefore, the modularity of the predictive polygon controller allows for the flexible application of various fictitious forces, making it adaptable to different control architectures, whether based on position or rate control, as well as measured or computed force feedback. It could serve as the underlying base controller for telenavigation, upon which other stability, multi-modal, or shared-control methods could be integrated, thereby demonstrating the robustness and effectiveness of it for real-world teleoperation tasks.

3. PASSIVE TELENAVIGATION INTERFACE

In the previous section, it was explained how the predictive polygon controller was applied specifically to a car-like WMR with a driving mechanism that matched well with the curvature commands given by a human operator. However, when extending this control method to other types of driving mechanisms, such as skid-steering WMRs, challenges arise due to differences in how curvature commands translate into the robot's actual movement. The polygon-based method does not map effectively to skid-steering systems, as the curvature commanded by the operator does not correspond accurately to the WMR's actual turning direction. This mismatch forces the operator to rely heavily on visual feedback to compensate for the WMR's heading, which complicates control and can compromise collision avoidance. In this section, we propose modifying the predictive polygon-based controller to include curvature command scaling, enabling the human operator to adapt the input to better match the turning radius of a skid-steering WMR. It will be shown that this approach maintains passivity, thereby ensuring stable bilateral teleoperation, even in the presence of unknown communication delays.

Haptic Interface

The haptic interface used for telenavigation of a skid-steering WMR consists of two 1-DoF rotational haptic devices (Fig. 3(a)), which allow human operators to control the WMR's steering. The angular range used was from 0° to 135° , providing a wide, intuitive control space for operators to steer the WMR either left or right. A foot pedal (Fig. 3(b)), similar

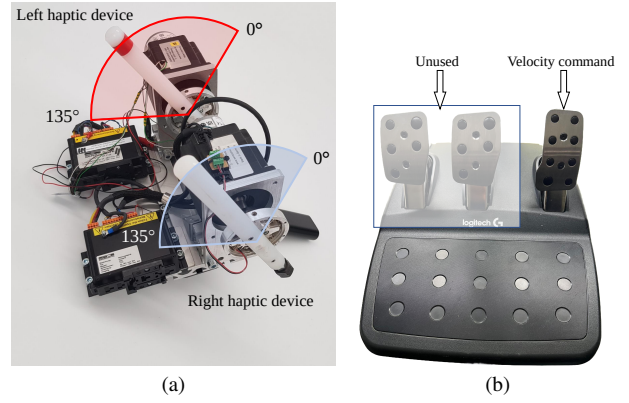


Figure 3. (a) Two 1-DoF haptic devices used to command curvatures to the skid-steering WMR. (b) Foot pedal used to command velocity to the WMR.

to those used in automobiles, is employed to control the velocity of the WMR, enabling operators to modulate speed while steering with the haptic devices.

When both haptic devices are positioned at the 0° mark, their starting position, the WMR does not receive any turning input and moves straight when the foot pedal is pressed. Pulling the left haptic device towards the operator while keeping the right device in the neutral position skews the WMR to the left. Conversely, pulling the right haptic device while leaving the left device neutral causes the WMR to turn right. The degree of turning is directly proportional to how much the haptic device is rotated—if one device is fully rotated to 135° while the other remains at zero, the WMR rotates on spot. If both haptic devices are rotated back with non-zero angles, the WMR is again commanded to move straight.

These direction commands, generated by the haptic devices, serve as curvature inputs for the predictive polygon method used in controlling the WMR's movement. The system also incorporates persuasive fictitious force-feedback from the virtual environment's danger map, providing the operator with feedback on potential obstacles on the course. The feedback is generated by calculating overlapping region between direction-dependent curvature polygons P_L and P_R , which represent the left and right curvatures, and obstacles identified in the environment via stereo vision. The danger map assigns a binary danger index $D(x, y)$ to each pixel around the WMR, 0 if there is no obstacle (green colored pixels in Fig. 2), 1 if there is (red colored pixels in Fig. 2). The force-feedback components F_d are computed based on the total overlap between the polygons and the danger areas, and a scaling factor k_p .

$$F_d \propto \sum_{(x,y) \in P_d} k_p \cdot D(x, y) \quad \text{for } d = R, L \quad (1)$$

This system ensures that the operator receives haptic feedback, allowing them to make informed decisions about the robot's navigation, even in complex and obstacle-laden environments.

Passive predictive polygon with position scaling framework

Fig. 4 illustrates the signal flow diagram of a delayed predictive polygon-based bilateral teleoperation system, where the variables T_f and T_b represent the forward and backward communication delays, respectively. In this setup, the haptic devices send curvature commands that define the robot's

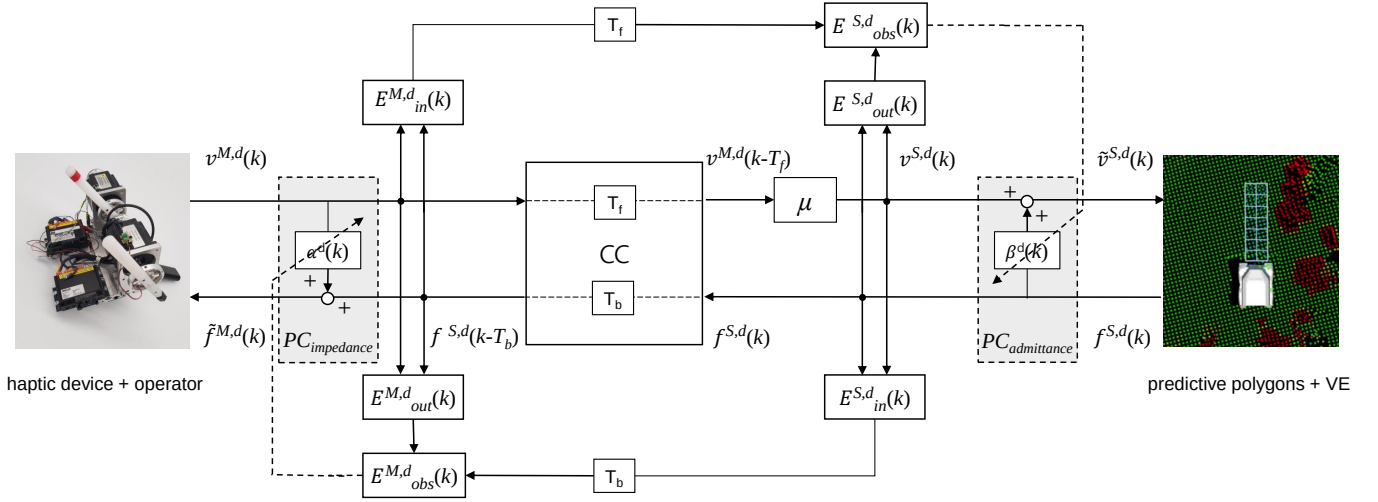


Figure 4. Signal flow diagram of passive predictive polygon method with scaling factor μ .

movement, but these commands, denoted as $v^{M,d}$, only reach the WMR after a delay T_f . These delayed curvature inputs cause the predictive polygons, representing the robot's motion path, to shift accordingly. When these polygons overlap with obstacles in the danger map, a fictitious force is generated, which is then relayed back to the human operator via the haptic interface, also after a delay T_b , providing essential force feedback.

However, one of the challenges is its inherent vulnerability to instability due to the communication delays. These delays can lead to a non-passive CC, which may destabilize the teleoperation system. As outlined in [24], ensuring the passivity of the two-port CC is a critical condition for achieving stable bilateral teleoperation. The TDPA addresses this issue by introducing adaptive virtual damping elements, which are deployed both at the haptic interface and on the robot's side, which for the remainder of the paper will be termed as main and secondary sides. These damping elements are placed in series and parallel configurations, dynamically dissipating just the right amount of energy to stabilize the entire teleoperation system, even in the presence of communication delays.

A sufficient condition to satisfy the passivity requirement, particularly under conditions of communication delays, is given by:

$$E_{obs}^{M,d}(k) = E_{in}^{S,d}(k - T_b) - E_{out}^{M,d}(k) \geq 0, \forall k \geq 0, \quad (2)$$

$$E_{obs}^{S,d}(k) = E_{in}^{M,d}(k - T_f) - E_{out}^{S,d}(k) \geq 0, \forall k \geq 0, \quad (3)$$

where, $E_{in}^{M,d}(k)$, $E_{out}^{M,d}(k)$, $E_{in}^{S,d}(k)$, and $E_{out}^{S,d}(k)$ are non-negative, monotonically increasing functions, representing the energy flow in and out of the main (M) and secondary (S) sides of the CC. $E_{obs}^{M,d}(k)$ and $E_{obs}^{S,d}(k)$ denote the observed energy flows on the respective sides of the CC. Both conditions are sufficient to ensure passivity of the delayed teleoperation system [24].

The real-time assessment of the observed passivity conditions, as specified in (2) and (3), is carried out by the POs, which monitor the energies $W^{M,d}$ and $W^{S,d}$ on the main and

secondary sides.

$$W^{M,d}(k) = E_{in}^{S,d}(k - T_b) - E_{out}^{M,d}(k) + E_{PC}^{M,d}(k - 1), \quad (4)$$

$$W^{S,d}(k) = E_{in}^{M,d}(k - T_f) - E_{out}^{S,d}(k) + E_{PC}^{S,d}(k - 1), \quad (5)$$

where, $E_{PC}^{M,d}(k - 1)$ and $E_{PC}^{S,d}(k - 1)$ are the energies dissipated by the main and secondary PCs up to the previous time step.

Now when the position command is scaled down by μ on the secondary side, so are the powers and therefore energies $E_{in}^{S,d}(k - T_b)$ and $E_{out}^{S,d}(k)$, when compared to non-scaled energy values.

$$E_{in/out}^{S,d}(k) = \Delta T \sum_{k=0}^n f^{S,d}(k) \cdot \dot{x}^{S,d}(k) \quad (6)$$

where, $x^{S,d}(k) = \mu \cdot x^{M,d}(k - T_f)$, and ΔT is the sampling time. It should be noted that since the scaling is only added to the delayed position on the secondary side, the energy on the main side, namely $E_{in}^{M,d}(k - T_f)$ and $E_{out}^{M,d}(k)$, remain unaffected.

The passivity controllers are adaptive energy-dissipating elements that dissipate any excess energy identified by the POs. As depicted in Fig. 4, the PC is applied in both impedance (main side) and admittance (secondary side) configurations within a Position-Force computed (P-Fc) architecture of the predictive polygon method.

$$\alpha^d(k) = \begin{cases} \frac{W^{M,d}(k)}{\Delta T (v^{M,d})^2(k)}, & \text{if } W^{M,d}(k) < 0 \text{ and } v^{M,d}(k) \neq 0 \\ 0 & \text{else} \end{cases} \quad (7)$$

$$\beta^d(k) = \begin{cases} \frac{W^{S,d}(k)}{\Delta T (f^{S,d})^2(k)}, & \text{if } W^{S,d}(k) < 0 \text{ and } f^{S,d}(k) \neq 0 \\ 0 & \text{else} \end{cases} \quad (8)$$

where, α and β are adaptive damping elements that dissipate the extra generated energy, thereby guaranteeing the passivity

conditions presented in (2) and (3). The impedance-type PC modifies the delayed feedback force to the main side and the admittance-type PC modifies the delayed reference velocity to the secondary side.

$$\tilde{f}^{M,d}(k) = f^{S,d}(k - T_b) + \alpha^d(k)v^{M,d}(k) \quad (9)$$

$$\tilde{v}^{S,d}(k) = \dot{x}^{S,d}(k) + \beta^d(k)f^{S,d}(k) \quad (10)$$

where, $\tilde{f}^{M,d}(k)$ is the modified force to the main device, and $\tilde{v}^{S,d}(k)$ is the adjusted velocity reference to the secondary device.

Since the position is scaled down, the $E_{out}^{S,d}(k)$ will be smaller than non-scaled value and therefore the admittance PC on the secondary side will be triggered less often. This will reduce the artifact of admittance PC, which is position drift. So, now the predictive polygons can overlap more with the obstacles in the danger map, generating higher fictitious forces cued to the human operator. On the main side, the effect of this scaling is that $E_{in}^{S,d}(k - T_b)$ is also smaller than non-scaled value, which will result in the impedance PC triggering more often. The artifact of impedance PC is high frequency force chattering, which can be improved using a virtual mass-spring filter [25] or chattering-free approach [26].

The proposed framework for predictive polygon method with position scaling can be used as a base controller for telenavigation of skid-steering WMRs. It could be adaptive in nature where based on the sensory information, the scaling gets modified to better match the command to reference curvature without violating passivity. Therefore, it guarantees stability, along with reducing position drift which can result in better estimation of obstacles in the WMR's vicinity due to higher fictitious forces generated due to more overlap of the polygons with the obstacles in the danger map.

The following section will demonstrate experimental validation of stability and performance through position, force and energy plots.

4. EXPERIMENTAL EVALUATION

Experimental Setup

Figure 3 shows the two 1-DoF rotational devices used as haptic input devices to command curvature to the predictive polygon and the foot pedal used to command velocity to the WMR. Both have a sampling rate of 100 Hz. To have a visual feedback, three low-latency image streams from cameras were used, front-left, front-center and front-right. Depth data from the eight cameras clustered into four stereo pairs, one on each side of the WMR, was used to build the danger map, that determines the traversability [17]. The user interface for the setup is shown in Fig. 5. The three low-latency camera streams are shown on top and the danger map is displayed below to provide a convenient overview to the operator of the WMR's surroundings.

Results

The proposed controller was evaluated through a series of experiments in which a human operator used one of the haptic devices to command curvature to the predictive polygon method, guiding the robot towards an obstacle in the danger map (see Fig. 5). The telenavigation setup had a minimal inherent delay of less than 10 ms due to the wireless communication setup. In these experiments, the operator made few contacts with an obstacle, and corresponding position, force, and energy data are plotted.

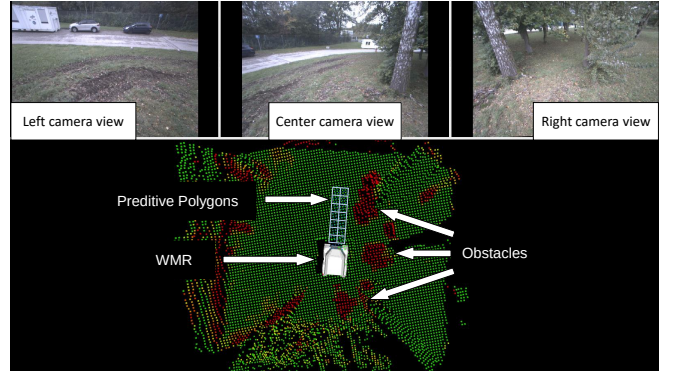


Figure 5. The user interface for the experimental setup. The camera views from the WMR is shown at the top, and the danger map showing the schematic of WMR with predictive polygon method is displayed at the bottom.

For the case where the position scaling factor $\mu = 1$ and the delay is less than 10 ms (Fig. 6), the system remains inherently stable, even in the absence of a passivity-based stabilizing controller. In this configuration, the polygons contact the obstacle at a curvature command of 0.1 from the haptic device. The forces on both the robot and haptic device sides shows a high degree of correspondence, as the minimal delay does not significantly alter the force feedback needed for system stability. The energy plots further confirm that the system remains passive, with $E_{in}^{M,S}(k - T_{f,b}(k)) \geq E_{out}^{S,M}(k)$, which ensures stable operation.

To test the robustness of the controller, a significant communication delay of $1000 \text{ ms} \pm 5 \text{ ms}$ round-trip (rt) was introduced. Even for well-tuned systems, such a large time delay typically leads to instability.

For $\mu = 1$ with a $1000 \text{ ms} \pm 5 \text{ ms}$ delay (Fig. 7), the admittance PC response can be observed in the position plots through the noticeable position drift between the commanded curvature from the haptic device and the actual curvature of the polygons when they contact the obstacle. It should be noted that no fictitious force is generated until the polygons overlap with an obstacle. Therefore, during the instance of no overlap, the fictitious force will be 0, and therefore, there will be no power flow in the network and no PC activity. This would result in no visible position drift between the commanded curvature of the haptic device and the reference curvature to the WMR. However, as soon as fictitious force is non-zero, the action of admittance PC may start introducing position drift. The impedance PC action is evident in the force plots, where the force feedback exhibits high-frequency chattering. The energy plots demonstrate that the CC remains passive, with the POs monitoring excess activity and PCs dissipating it.

When $\mu = 0.6$ and the same $1000 \text{ ms} \pm 10 \text{ ms}$ delay is applied, as shown in Fig. 8, notable differences arise compared to the $\mu = 1$ case. Contact with the obstacle requires a higher curvature command from the haptic device, because the position is scaled down on the secondary side. This should not be mistaken with position drift which is an artifact of the admittance PC. However, once contact is made (the polygons overlap the obstacle in the danger map), position drift is relatively reduced compared to $\mu = 1$. This reduction occurs because $\mu = 0.6$ leads to a lower $E_{out}^{S,d}(k)$, meaning the admittance PC triggers less frequently, resulting in less dampening of the velocity command. Consequently, this would allow for greater

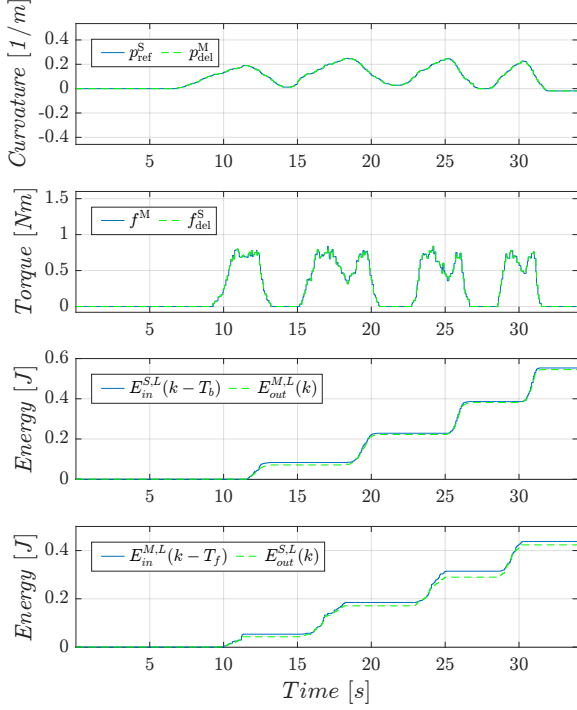


Figure 6. Experimental results for predictive polygon method with communication delay less than 10 ms.

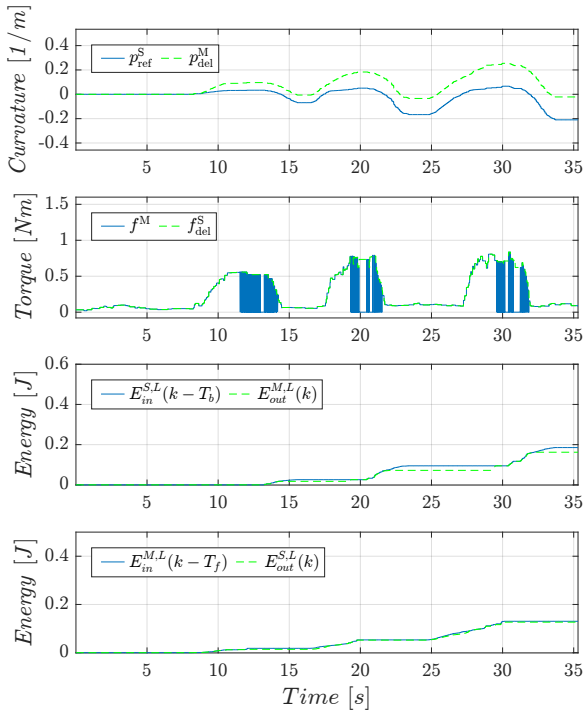


Figure 7. Experimental results for predictive polygon method with position scaling (μ) of 1 and round-trip communication delay of 1000 ms $\pm$ 5 ms.

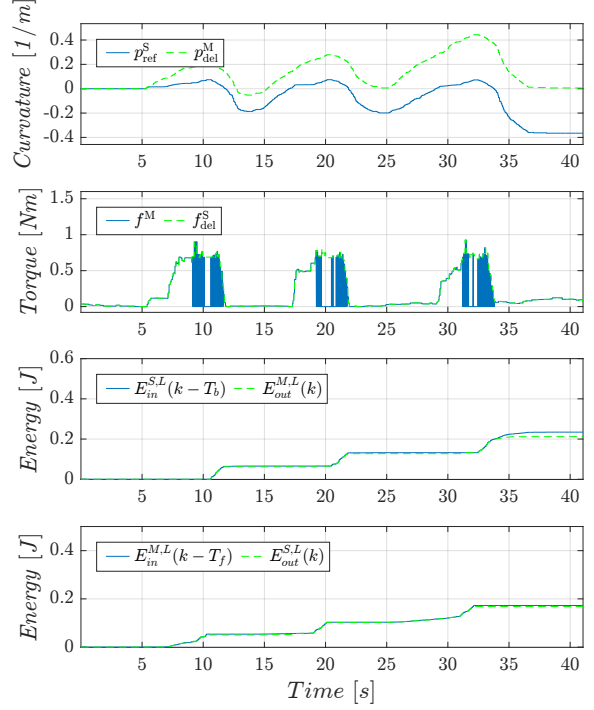


Figure 8. Experimental results for predictive polygon method with position scaling (μ) of 0.6 and round-trip communication delay of 1000 ms $\pm$ 5 ms.

overlap between the polygons and the obstacle, generating relatively higher fictitious force feedback. However, force chattering on the haptic device side may increase, as the lower $E_{in}^S(k - T_b)$ requires greater dissipation of $E_{out}^M(k)$, leading to more pronounced chattering. Despite these artifacts, the energy plots confirm that the telenavigation system remains stable.

These experiments demonstrate the effectiveness of the predictive polygon controller with position scaling. Importantly, adjusting the scaling factor μ does not introduce instability into the system, as long as it is accounted for in the PO and PC. This flexibility allows the human operator to manually adjust or adaptively modify the scaling, ensuring that the commanded curvature to the polygons matches the skid-steering WMR's actual turning radius. Consequently, this approach provides meaningful force feedback, enabling the operator to avoid obstacles and navigate safely without compromising system stability.

5. CONCLUSION AND FUTURE WORK

This work presents a framework for teleoperating skid-steering WMRs using the predictive polygon method with position scaling μ . The operator's commanded curvature could be modified based on the scaling value in a passive manner even in the presence of delay, such that it matches the turning radius of the skid-steering WMR. The haptic interface consists of two rotational 1-DoF devices, which allow the operator to command the robot's curvature, and a foot pedal that controls velocity, providing a familiar and effective means of interaction. The fictitious force feedback computed from the polygon's overlap with the obstacles in

the danger map, further enhances the operator's ability to telenavigate.

Experimental results demonstrate the effectiveness of this approach under different delay conditions and scaling factors. For a communication delay = $1000 \text{ ms} \pm 5 \text{ ms}$ and $\mu = 1$, the system exhibited noticeable position drift between the operator's commanded curvature and the reference curvature to the WMR, only during the polygon's overlap with the obstacle. This drift, along with force chattering, is an artifact of the TDPA, which can be compensated by introducing virtual damping to preserve system passivity. The system was stable, with the human operator being able to perceive the obstacles via delayed force feedback. Introducing $\mu = 0.6$ under the same delay resulted in relatively reduced position drift, as the lower scaling factor reduced the E_{out}^S , causing the admittance passivity controller to intervene less frequently. This reduced position drift would allow for higher overlap between the predictive polygons and virtual obstacles, generating more pronounced fictitious forces. However, this would result in increased force chattering on the haptic device side, as lower E_{in}^S required more aggressive energy dissipation on the haptic device side. Despite this, the system remained stable, with energy plots confirming passivity.

The predictive polygon method with position scaling, provides a framework which can be further explored in future works. Adaptive position scaling could be integrated based on sensory information for the commanded curvature to match WMR's curvature while delivering corrective forces to the operator. Predictive polygon teleoperation with position and force scaling can also be exploited for better position accuracy or force feedback, based on the task at hand.

ACKNOWLEDGMENT

We gratefully acknowledge the funding provided by the DLR and the "Bavarian Ministry of Economic Affairs, Regional Development and Energy" for the AHEAD (autonomous humanitarian emergency aid devices) Project frame including the projects MaiSHU, KI4HE, MUSERO, RESITEK and the HGF funded sustainability challenge project iFOODis KA-HSC-06 iFOODis.

REFERENCES

- [1] H. Singh, M. Panzirsch, A. Coelho, and C. Ott, "Proxy-based approach for position synchronization of delayed robot coupling without sacrificing performance," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6599–6606, 2020.
- [2] H. Singh, A. Jafari, and J.-H. Ryu, "Enhancing the force transparency of time domain passivity approach: Observer-based gradient controller," in *2019 International Conference on Robotics and Automation (ICRA)*. IEEE, 2019, pp. 1583–1589.
- [3] M. Panzirsch, A. Pereira, H. Singh, B. Weber, E. Ferreira, A. Gherghescu, L. Hann, E. den Exter, F. van der Hulst, L. Gerdes *et al.*, "Exploring planet geology through force-feedback telemanipulation from orbit," *Science robotics*, vol. 7, no. 65, p. eabl6307, 2022.
- [4] X. Xu, M. Panzirsch, Q. Liu, and E. Steinbach, "Integrating haptic data reduction with energy reflection-based passivity control for time-delayed teleoperation," in *2020 IEEE Haptics Symposium (HAPTICS)*. IEEE,

- 2020, pp. 109–114.
- [5] M. Panzirsch, H. Singh, and C. Ott, "The 6-dof implementation of the energy-reflection based time domain passivity approach with preservation of physical coupling behavior," *IEEE Robotics and Automation Letters*, vol. 5, no. 4, pp. 6756–6763, 2020.
- [6] T. Hulin, M. Panzirsch, H. Singh, A. Coelho, R. Balachandran, A. Pereira, B. M. Weber, N. Bechtel, C. Riecke, B. Brunner *et al.*, "Model-augmented haptic telemanipulation: concept, retrospective overview, and current use cases," *Frontiers in Robotics and AI*, vol. 8, p. 611251, 2021.
- [7] H. Singh, D. Janetzko, A. Jafari, B. Weber, C.-I. Lee, and J.-H. Ryu, "Enhancing the rate-hardness of haptic interaction: successive force augmentation approach," *IEEE Transactions on Industrial Electronics*, vol. 67, no. 1, pp. 809–819, 2019.
- [8] C. Riecke, B. Weber, M. Maier, M. Stelzer, R. Balachandran, A. Kondratiev, A. Vasiliev, A. Sergeev, V. Dubinin, and O. Rudakova, "Kontur-3: Human machine interfaces for telenavigation and manipulation of robots from iss," in *2020 IEEE Aerospace Conference*. IEEE, 2020, pp. 1–10.
- [9] W. Li, Y. Liu, L. Ding, J. Wang, H. Gao, and Z. Deng, "Teleoperation of wheeled mobile robots subject to longitudinal slipping and lateral sliding by time-domain passivity controller," *Mechatronics*, vol. 81, p. 102705, 2022.
- [10] M. Sajjadi, M. Chahari, and H. Salarieh, "Haptic tele-driving design of vehicle steering control system with communication delay under complicated driving and road conditions," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, p. 09544070241261111, 2024.
- [11] W. Li, L. Ding, H. Gao, and M. Tavakoli, "Haptic tele-driving of wheeled mobile robots under nonideal wheel rolling, kinematic control and communication time delay," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 50, no. 1, pp. 336–347, 2017.
- [12] Y. Dong and N. Chopra, "Passivity-based bilateral tele-driving system with parametric uncertainty and communication delays," *IEEE Control Systems Letters*, vol. 3, no. 2, pp. 350–355, 2018.
- [13] K.-W. Lee, D.-K. Ko, Y.-J. Kim, J.-H. Ryu, and S.-C. Lim, "Latency-free driving scene prediction for on-road tele-driving with future-image-generation," *IEEE Transactions on Intelligent Transportation Systems*, 2024.
- [14] J. Artigas, R. Balachandran, C. Riecke, M. Stelzer, B. Weber, J.-H. Ryu, and A. Albu-Schaeffer, "Kontur-2: force-feedback teleoperation from the international space station," in *2016 IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, 2016, pp. 1166–1173.
- [15] H. Van Quang, I. Farkhatdinov, and J.-H. Ryu, "Passivity of delayed bilateral teleoperation of mobile robots with ambiguous causalities: Time domain passivity approach," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 2635–2640.
- [16] M. Panzirsch, H. Singh, T. Krüger, C. Ott, and A. Albu-Schäffer, "Safe interactions and kinesthetic feedback in high performance earth-to-moon teleoperation," in *2020 IEEE Aerospace Conference*. IEEE, 2020, pp. 1–10.
- [17] C. Brand, M. J. Schuster, H. Hirschmüller, and

M. Suppa, “Stereo-Vision Based Obstacle Mapping for Indoor / Outdoor SLAM,” in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Chicago, Illinois, USA, 2014.

- [18] M. Panzirsch, H. Singh, M. Stelzer, M. J. Schuster, C. Ott, and M. Ferre, “Extended predictive model-mediated teleoperation of mobile robots through multi-lateral control,” in *2018 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, 2018, pp. 1723–1730.
- [19] M. Sierotowicz, B. Weber, R. Belder, K. Bussmann, H. Singh, and M. Panzirsch, “Investigating the influence of haptic feedback in rover navigation with communication delay,” in *Haptics: Science, Technology, Applications: 12th International Conference, EuroHaptics 2020, Leiden, The Netherlands, September 6–9, 2020, Proceedings 12*. Springer, 2020, pp. 527–535.
- [20] E. Slawiński, F. Rossomando, F. A. Chicaiza, J. Moreno-Valenzuela, and V. Mut, “Lstm network in bilateral teleoperation of a skid-steering robot,” *Neurocomputing*, vol. 602, p. 128248, 2024.
- [21] K. Kozłowski and D. Pazderski, “Modeling and control of a 4-wheel skid-steering mobile robot,” *International journal of applied mathematics and computer science*, vol. 14, no. 4, pp. 477–496, 2004.
- [22] S. Coloma, C. Martinez, B. C. Yalçın, and M. A. Olivares-Mendez, “Enhancing rover teleoperation on the moon with proprioceptive sensors and machine learning techniques,” *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 11 434–11 441, 2022.
- [23] M. Panzirsch and R. Balachandran, “Time domain control for passive variable motion and force scaling in delayed teleoperation,” *IFAC-PapersOnLine*, vol. 52, no. 18, pp. 31–36, 2019.
- [24] J.-H. Ryu and C. Preusche, “Stable bilateral control of teleoperators under time-varying communication delay: Time domain passivity approach,” in *Proceedings 2007 IEEE international conference on robotics and automation*. IEEE, 2007, pp. 3508–3513.
- [25] J.-H. Ryu, J. Artigas, and C. Preusche, “A passive bilateral control scheme for a teleoperator with time-varying communication delay,” *Mechatronics*, vol. 20, no. 7, pp. 812–823, 2010.
- [26] H. Choi, R. Balachandran, and J.-H. Ryu, “Chattering-free time domain passivity approach,” *IEEE Transactions on Haptics*, vol. 15, no. 3, pp. 572–581, 2022.

BIOGRAPHY



Harsimran Singh received his B.Tech degree in electrical and electronics engineering from Sikkim Manipal Institute of Technology in 2009, and M.Sc. in robotics from the University of the West of England in 2012. In 2017, he received his Ph.D. degree in mechanical engineering from Korea University of Technology and Education. He is currently a research scientist with the Institute of Robotics and Mechatronics at German Aerospace Center (DLR). His current research interests include control and stability in robotics, haptics, teleoperation, and shared autonomy.



Michael Panzirsch received his diploma in mechanical engineering from the Technische Universität München in 2010. Since then he is with the Department for Analysis and Control of Advanced Robotic Systems of the German Aerospace Center (DLR) in Oberpfaffenhofen as a research associate. He finished his Ph.D. thesis on passivity-based multilateral control for delayed teleoperation at the Polytechnical University of Madrid (UPM) in October 2018. His main areas of research interests are teleoperation of robotic manipulators and mobile robots, haptics and healthcare robotics. Currently, he is working on topics as Haptic Augmentation, Model-Mediated Teleoperation and Elasto-Plastic Robot Compliance.



Mallikarjuna Vayugundla is a senior research engineer at the Institute for Robotics and Mechatronics at DLR (German Aerospace Center), where he works on mapping and navigation algorithms for autonomous robotic systems. His research focuses on enabling robots to navigate and operate effectively in complex planetary environments, such as the Moon and Mars. He joined DLR as a full-time researcher in 2016 after receiving his Master's degree in Autonomous Systems from Bonn-Rhine-Sieg University of Applied Sciences in 2015.



Yunis Scheeler works at the Institute for Robotics and Mechatronics at the German Aerospace Center (DLR) as a scientific researcher since 2020. He received his M.Sc. degree in electrical engineering from the Technical University of Munich in 2019 with the specialization on robotics and automation. His research focuses on the topic of semantic mapping in distributed robotic systems.



Martin J. Schuster is senior researcher and leader of the Rover Exploration team at the Institute of Robotics and Mechatronics of DLR. He received his Ph.D. (Dr.-Ing.) degree in Computer Science (CS) from the University of Bremen in 2019, his first Master's degree in CS from the Georgia Institute of Technology in Atlanta, USA in 2010, his Bachelor's and second Master's degree in CS from the Technical University of Munich in 2008 and 2011, and his Bachelor's degree in Philosophy from the Ludwig-Maximilians-Universität München (LMU) in 2014. His research focus is on multi-robot SLAM in GNSS-denied areas.



Riccardo Giubilato is a senior researcher and leader of the Intelligent Exploration and Mapping group at the Institute of Robotics and Mechatronics, German Aerospace Center (DLR), Weßling, Germany. In 2020 he received a Ph.D. from Centre of Studies and Activities for Space (CISAS) “G. Colombo,” University of Padova. His current research interests include sensor

fusion for vision systems and range sensors, visual SLAM, multi-agent localization and mapping.



Ribin Balachandran received a bachelor degree in Electrical and Electronics Engineering from National Institute of Technology Surathkal, India in 2009 and a master degree in Automation and Robotics from Technical University of Dortmund, Germany in 2012. From 2013 to 2025, he worked as a researcher at the department for “Analysis and Control of Advanced Robotic Systems”

in the Institute of Robotics and Mechatronics, German Aerospace Center (DLR). His main research areas are time-delayed teleoperation, haptics and control for robotics. He finished his Ph.D. thesis on ‘A stable and transparent framework for adaptive shared control of robots’ at the Technical University of Munich (TUM) in May 2022.

supply chains and agriculture to combat climate change and improve food production. With the coordination of the AHEAD (autonomous humanitarian emergency aid devices) Project within (DLR). At the HGF funded iFOODis project (2023-2027), he will focus the work on intelligent robotic systems to increase sustainability of food cycles.



Jörg Langwald is senior research scientist at the Institute of Robotics and Mechatronics of the German Aerospace Center (DLR). His research interests include computer vision for mobile robots, especially FPGA based image processing and embedded computing. He received his Dipl.-Ing. degree in electrical engineering in 1995 from the Ilmenau University of Technology, Germany.



Harald Wagner works at the Institute for Robotics and Mechatronics at the German Aerospace Center (DLR) as head of mechanical CAD/CAM production at the RM Institute since 1990. Construction of various robot joints, some for space use.



Thomas Hulin received his Dipl.-Ing. degree in electrical engineering from the Technical University of Munich (TUM) in 2003, and the Dr.-Ing. degree in mechanical engineering from the Leibniz University of Hannover (LUH) in 2017. He joined the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR) in 2003 as a research associate and heads the Telemanipulation

Research Group since 2020. His research interests include haptics (control, devices, and algorithms), telerobotics, physical human-robot interaction, robot visualization, augmented reality, and skill transfer.



Armin Wedler is Head of Planetary Exploration and Field Robotics at DLR Institute of Robotics and Mechatronics, studied mechanical engineering and robotics and has a doctorate on “Adaptive passive compliant systems for use in robotics” from the University of Hannover. He works at DLR since 2008. Within his work, Mr. Wedler aims to support sustainable technologies for hu-

manity, including the use of robots in crisis regions, food