Mixed-initiative Dynamic Autonomy Through Variable Levels of Immersion and Control (MIDA-VIC): A new Paradigm for Collaborative Robotic Teleoperation in Space Exploration

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Abstract

In this position paper, we propose the new control paradigm and conceptual framework MIDA-VIC for collaborative robotic teleoperation in space exploration and beyond. Such teleoperation is a complex and demanding team effort with distributed responsibilities that require both efficient human-robot and human-human collaboration. To address these challenges, we propose a new paradigm of mixed-initiative dynamic autonomy for robotic teleoperation. It exploits recent advances in human-computer interaction (HCI), human-robot interaction (HRI), augmented and virtual reality (AR/VR), and artificial intelligence (AI) research. By integrating methods from multiple fields, our paradigm allows human operators to choose their preferred level of immersion, from traditional 2D graphical user interfaces (GUIs) to fully immersive AR/VR environments. It also supports a dynamic adjustment of the level of control, ranging from direct motor commands (e.g., using a joystick) to high-level task delegation using AI (e.g., instructing the robot via natural language to select a path or explore autonomously). In addition, we propose a mixed-initiative paradigm in which a robot can also take the initiative, request human assistance, and propose the specific level of immersion and control to the human operator that it currently considers useful for effective and efficient collaboration.

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1 Introduction

The teleoperation of a complex robotic system is a demanding team activity. This is especially true for a space telerobot, which is a remotely operated robot that performs work in a rich space environment that could include the unstructured surface of a planet or asteroid, or complex operational settings such as on-orbit servicing of a satellite [13]. Human operators in a command center for space telerobots must deal with multiple challenges such as long communication delays, incomplete and uncertain information from sensors or cameras, and changing requirements for the level of control, ranging from low-level direct control of

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motors and nonautonomous functions to high-level supervisory control of (semi)autonomous processes. Missions involving Lunar or Mars rovers require multiple operators to manage and supervise these partially autonomous systems, ensuring that operational goals are met while maintaining the health of the rover and its science payloads [16]. Typically, human operators assume various specialized roles to ensure the successful teleoperation of robotic rovers. The following real-world examples, which were simplified for the purpose of this paper, illustrate the typical complexity and breadth of involved roles:

- *Command and Control Operators:* These individuals are responsible for sending movement commands to the rover, such as navigation paths and manipulator operations. They utilize real-time data and pre-planned sequences to guide the rover's actions. For example, command operators ensure that the rover safely follows planned traverses and maneuvers within time and power constraints.
- *System Health Monitors:* Dedicated engineers continuously observe the rover's telemetry and subsystem status to maintain its health. They track critical metrics including power levels, temperatures, communication signal strength, and motor currents. For instance, mission teams often assign specialists to monitor system or payload health (battery, instruments, etc.) and flag any issues.
- *Science Team Members:* These experts analyze data collected by the rover's instruments, such as imagery and spectroscopic readings, to make scientific interpretations and decisions about future exploration targets.
- *Communication Specialists:* Given the significant communication delays in space missions, these operators manage the scheduling and transmission of data between the rover and Earth, ensuring synchronization and data integrity.

To address these multiple challenges and roles in space human-robot interaction, this position paper proposes the new MIDA-VIC conceptual framework for **m**ixed-**i**nitiative **d**ynamic **a**utonomy through **v**ariable levels of **i**mmersion and **c**ontrol. We explain the different components of the proposed framework and illustrate how it can be used to envision future control systems for space telerobots. By this, we lay the foundation for future research on MIDA-VIC to build prototypes of future collaborative systems for robotic teleoperation and to collect empirical data about their benefits from user studies.

2 Background and Related Work

The MIDA-VIC control paradigm is based on three key concepts that we elaborate in the following: (1) *situation awareness* as an overall design goal for collaborative control systems, (2) *variable levels of immersion* for human-robot interfaces, and (3) *variable level of control* that human controllers exert over an non-/semi- or fully autonomous telerobot.

2.1 Situation Awareness

Given the complex and collaborative nature of robotic teleoperation in space exploration, research in human factors (HF), human-computer interaction (HCI), and human-robot interaction (HRI) has aimed to reduce the mental, physical, and temporal demands of teleoperation. For example, innovative designs of user interfaces, visualizations, interaction techniques, and control room layouts are intended to leave teams with more mental, physical, and temporal resources to develop a good collective *situation awareness* (SA).

SA is commonly defined after Mica R. Endsley as "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" [8]. In other words, SA is a person's real-time understanding of "what is going on" around them and what might happen next. Endsley's model breaks SA into three levels that can be applied to our telerobotic scenario:

- Level 1: *Perception* – Being aware of the relevant cues in the environment. For a rover operator, this means perceiving key data from the robot and its surroundings: e.g. receiving camera images, seeing obstacle locations, reading the rover's speed, battery level, or telemetry warnings. Without perceiving these status elements, an operator cannot move to higher awareness.
- Level 2: *Comprehension* – Understanding what those perceived elements mean in context. In teleoperation, the operator must interpret the sensor data correctly – for instance, recognizing that "the rover's wheel slip is high", which could indicate that the terrain is soft sand. Alternatively, a certain rock in the camera view might be a science target of interest. Comprehension implies that the operator synthesizes different data points into a holistic picture ("the rover is tilted on a slope and losing traction"). This level of awareness allows the human to assess the significance of the current situation relative to mission goals.
- Level 3: *Projection* – Anticipating the future status of elements in the environment. In the rover scenario, this is the ability to predict what will happen next: if the rover continues on its path, will it get stuck? If the battery is at 20% now, will it last through the next planned drive? Good SA means that the operator can project ahead a few minutes or hours based on the current trends. This foresight is critical for decision-making, such as planning maneuvers to avoid an obstacle or scheduling a return to base before sunset.

Endsley's framework is highly relevant in this context because teleoperators operate in dynamic environments (another planet's surface) where they must continuously perceive changes, understand their implications, and predict the outcomes to make correct decisions. However, achieving robust SA in a teleoperation setting is challenging. The operator is separated from the rover by distance and relies on information constrained by limited bandwidth, which can degrade awareness. Endsley and others point out several factors that can undermine situation awareness for remote operators: poor sensory information, communication delays, and interface complexity are all obstacles to building a clear picture [9].

2.2 Variable Levels of Immersion

Virtual Reality (VR) for robotic teleoperation in space has been proposed since the 1990s [5] and potentially improves SA by providing more sensory information and reducing interface complexity. However, isolating operators in VR from their real-world team members and command center can also undermine SA and efficient collaboration. In our own previous work on collaborative *Transitional Interfaces* [25] and using Augmented Reality (AR) for HRI [3], we have examined different strategies for immersive technologies that could support operators without such disadvantages.

For example, our research on Transitional Interfaces explores how 2D graphical user interfaces (GUIs) can be seamlessly integrated with AR and VR to support teams. We have examined new ways for human collaborators to use variable levels of immersion, i.e., seamlessly switching between (1) personal, immersive, and stereoscopic views with good depth perception in VR during spatial tasks, (2) less immersive, yet stereoscopic, 3D displays of spatial information in AR that do not isolate operators from their co-located human team members in the real world, or (3) "flat" 2D maps and charts on shared vertical or horizontal displays for efficient overview and group discussion. By this, we intend to better support teams during phases of tightly-coupled collaboration as well as more loosely-coupled parallel work and increase overall *workspace awareness* [25]. As we discuss in [24], technologies using variable levels of immersion could also help operators to better deal with communication latencies and asynchronous collaboration over long distances in space.

In HRI, we have explored approaches to increase SA by providing the operator with contextual visual information that augments the robot in such teleoperation scenarios. In particular, we were able to show how such visual augmentations can improve the user's ability to perceive and comprehend the robot's position with respect to its surroundings and potential target objects [3]. We also found a clear trade-off regarding visual complexity that needs to be taken into account when designing such augmentation [4]. Regarding the third level of SA – Projection, a literature review on understanding robot intent has shown that it is imminent to communicate not only motion but also current state or guide the user's attention [21]. It also showed that the level of immersion can vary quite a bit between different communication strategies, ranging from direct LED feedback on-robot joints [26] to visual path predictions in AR/VR [27], which all come with certain advantages and drawbacks, highlighting the need for variable levels of immersion. Regarding the question of how to realize such variable levels of immersion, we developed the AdaptiX framework, which provides a technical architecture that allows HRI to be designed along the full Mixed-Reality Continuum [20].

2.3 Variable Levels of Control

Good situation awareness, including projection and anticipation of future states of the environment as well as the individual actors, is vital for the teleoperation of robots due to the roundtrip communication delays of radio signals. These communication latencies are typically a few hundred milliseconds in low Earth orbit (LEO), but can reach between 5 to 14 seconds in Earth-Lunar or up to 40 minutes in Earth-Mars communication [19].

As latencies increase, control paradigms have to change as well. Manual control (or direct teleoperation), involving the complete control of the actuators on the robot by the operator, must be increasingly enhanced with supervisory control, in which the operator sends intermittent commands to a (semi-)autonomous robot and intervenes only when necessary. Manual and supervisory control may be utilized by the same telerobot, as evidenced by the popular Mars Curiosity Rover [15]. Due to the high latency of Mars communication, operators of Curiosity could choose between three layers of control to drive the rover [18], applying a concept also known as traded control [12]:

1. Low-level motor control commands that specify exactly how much to rotate each drive wheel and turn each steering wheel actuator.
2. Directed driving primitives for driving along circular arcs (of which straight-line driving and turn-in-place are special cases).
3. Autonomous path selection for reaching a goal while reacting to unexpected changes along the way.

Another perspective on these different layers is to look at the type of tasks the user takes on in such situations, i.e. rather on a strategic level (3) or more towards tactical (2) or operational (1) involvement. In particular, on the tactical and operational level, the possibility of shared control arises [11]. Such approaches aim to combine human input with robot operations without a clear traded control scheme, i.e., both operator and human act or respond, and the overall resulting action is a combination or fusion of these different inputs.

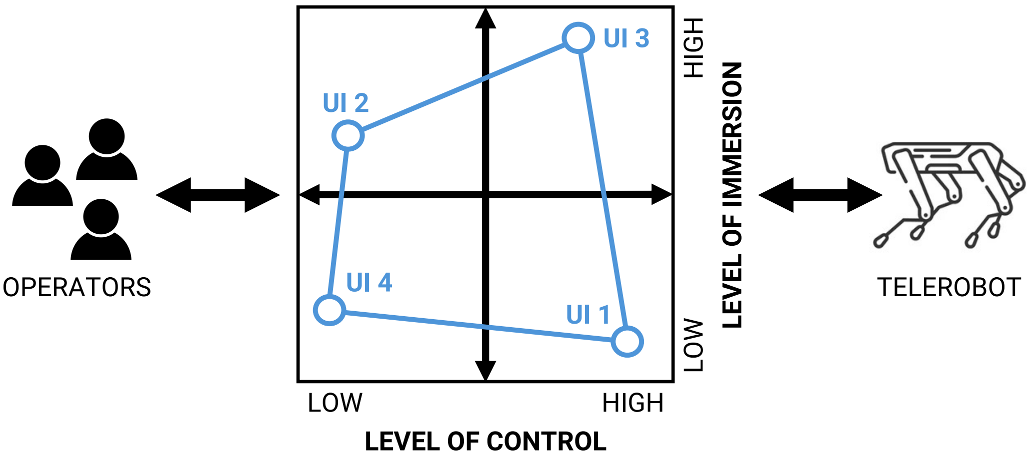

Figure 1 An illustration of the MIDA-VIC control paradigm. Co-located human operators in the control room are shown on the left and the telerobot for remote operation is on the right. Operators and telerobot communicate and collaborate via a set of connected user interfaces which are used in parallel inside the control room, e.g., UIs 1-4 (center). By switching between or adapting UIs, the human operators can dynamically adjust the current level of their control over the robot (horizontal axis) and the level of immersion (vertical axis) for each UI. By this, they can ensure that the robot's degree of autonomy, the visual representation of sensor data on the UI, input/output modalities for control, and UI complexity best meet the current task at hand and its situational needs.

Approaches from previous research and literature show that this can often be used to optimize human input through the use of machine learning and deep neural networks, e.g. CNNs [10, 22, 6, 23]. This shift necessitates the development of advanced human-robot autonomy frameworks [12, 1] but also mixed-initiative control strategies to maintain effective operation despite communication delays.

A possible direction in the context of variable control paradigms is the integration of Large Language Models (LLMs) to use natural language as a primary interface for human-robot communication [7, 2, 17]. With their ability to understand and generate context-aware dialogue, LLMs enable robots to be collaborative agents that are capable of participating in mission workflows as embodied conversational team members. Equipped with an LLM, a robot can report its internal state, explain its behavior, and reason about its environment using natural language. This enables a more natural interaction where operators can describe high-level goals or ask situational questions (e.g., "Are there any promising rock formations nearby?"), and the robot can respond accordingly (e.g., "I detected two interesting objects 15 meters northwest. Would you like me to investigate them?"). Such capabilities transform the robot into an active collaborator that can proactively provide suggestions, communicate uncertainties, or propose alternative aspects of the mixed-initiative paradigm that we propose. Future research should explore how LLMs can serve not only as conversational interfaces but also as reasoning layers for agent-like behavior in robotic systems. This includes dynamically adjusting language to support the operator's requirements, reasoning about high-level goals and constraints, and engaging in the negotiation of roles between humans and robots in long-term missions.

3 The MIDA-VIC Control Paradigm

Based on such previous work in HCI, HRI, AR/VR, and AI, we envision a new control paradigm for collaborative robotic teleoperation in space exploration and beyond. We refer to this paradigm as **m**ixed-**i**nitiative **d**ynamic **a**utonomy through **v**ariable levels of **i**mmersion and **c**ontrol (MIDA-VIC). The main components of MIDA-VIC are illustrated in Fig. 1.

MIDA-VIC enables multiple human operators to freely choose their individual *level of immersion*, ranging from conventional mouse- and keyboard-operated 2D graphical user interfaces to immersive, stereoscopic 3D visualizations in AR/VR with 3D input devices. It also allows them to dynamically adjust their *level of control*, ranging from low-level motor control commands, for example, with a joystick, to delegating high-level tasks such as autonomous path selection or autonomous exploration of an area to the robot, e.g., by conversing with the robot about its tasks, its status, and its progress in natural language. In consequence, the two-dimensional position between low and high levels of control (Fig. 1 horizontal axis) and low and high levels of immersion (Fig. 1 vertical axis) define the interaction style of how a operator and the telerobot temporarily communicate, interact, and collaborate. Multiple interaction styles can co-exist, so that operators 1-3 can each use their preferred interaction style(s) for collaborative teleoperation. They can always adjust their individual level of control and immersion to align it with their current role, responsibility, and goals. In addition, MIDA-VIC is a mixed-initiative paradigm [14] in which a robot can also take the initiative, request human assistance, and propose the specific level of immersion and control to the human operator that it currently considers useful for effective and efficient collaboration.

Example UI 1: A command and control operator could use the rather traditional UI 1 with low immersion and a high level of control (see Fig. 1) to manually adjust each joint or motor of a robot or to reset subsystems. UI 1's I/O devices, visualizations and interaction techniques are optimized for highly precise and direct interactions with a robot using a traditional mouse- and keyboard-operated control panel on a desktop screen with a 2D GUI containing sensor readings, logs, consoles, sliders, and input fields to enable high-precision adjustments and for identifying or addressing root causes of problems. UI 1 is the operators' obvious choice whenever they need to intervene in case of a failure of a high-level autonomous function or when the robot encounters an unexpected situation and asks for human assistance. It provides full and precise control but increases operators' mental and temporal demands.

Example UI 2: UI 2 is a high-immersion and low-level-of-control UI (see Fig. 1) that could be used by a science team member to supervise an automated 3D mapping process of the robot's environment and surrounding surface. This 3D reconstruction is generated through a highly automated process by continuously transmitting 360° camera images and laser distance measurements to the command center where the data is recorded, processed, and collated into a 3D reconstruction of the environment. For supervision of the process, the resulting map data is visualized as a steadily growing and increasingly detailed 3D map on an interactive multi-touch tabletop that enables operators to use gestures for moving, panning, and zooming their virtual camera to inspect data quality. Such a non-stereoscopic projection of automatically collected 3D data on a "flat" screen could be further enhanced by enabling operators to additionally wear an AR/VR head-mounted display (HMD), so that terrain data could additionally appear as stereoscopic AR "holograms" above or next to the tabletop. In some cases, operators could also decide to fully immerse themselves in a stereoscopic 3D VR visualization to "fly" through the data. Using AR/VR in this manner would move UI 2 further towards the top in Fig. 1.

Example UI 3: UI 3 with a high level of control and immersion becomes relevant when the robot's operation requires manual control of a mechanical subsystem, e.g., of a robotic arm in a challenging environment. For example, this could be picking up a geological sample from the ground while other rocks or rock formations are in close proximity and might also cover parts of a camera image. To help operators navigate the arm within a space that might also contain obstacles or is partially occluded, the UI ideally provides a stereoscopic display of a precise 3D reconstruction with good depth perception that can be used to plan, preview, and execute arm movements. Here, immersion is not only a question of visual output but also includes the possibility for physical and spatial input, e.g., by tracking human arm, hand, or controller movements in space.

Example UI 4: UI 4 uses voice I/O with natural language to enable hands-free and eyes-free human-robot control and communication. Thanks to rapid advances in AI, including natural language processing and reasoning with LLMs, this interaction style could become a powerful tool for efficient human-robot communication, despite its low level of control and immersion. For example, operators could verbally describe a desired target location or movement pattern to the robot as they would describe it to another human team member. This could also include instructions or informal "programming" of the robot to enable the robot to autonomously react to future events or changes in the environment, especially when human operators would be too slow to react due to communication delays. Using LLMs, UI 4 could also add a layer of high-level "natural" human-robot communication, during which the robot embodies an agent or team member. For example, the robot could provide status updates and reports in natural language that adapt to the situational needs and mental load of the human operators, e.g., in the amount of information, level of detail, and linguistic style. It will also be interesting to explore to what extent LLMs will enable agents to reason about the state of the robot and its environment in relation to its goals and will be able to come up with proposals for improving mission efficiency or solving critical challenges.

It is noteworthy, that UI 1-4 are just initial examples that we have developed to start further design explorations and that many other helpful configurations of input/output devices, modalities, and levels of control and immersion could become a part of future robotic teleoperation. Also, at the heart of the MIDA-VIC paradigm is the perspective that these styles will co-exist and will need to be used in parallel in order to address the complexity of robotic teleoperation in space.

4 Implications for Future Research

While there is a growing body of knowledge on successful and effective shared and traded control approaches, little is known about how different user interaction designs affect them. For example, previous research found that even very small changes at the presentation level of robot motion intent led to different perceptions of robot autonomy and potential for overtrust [22]. Adding to this, while there are numerous ways to communicate between robot and human, both to express intent or to control, there is a lack of systematic analysis and comparison. For example, research on robot intent identified a clear research gap in terms of theory building and design principles based on empirical data to better understand the benefits and drawbacks of certain approaches in comparison to each other [21].

Using Transitional Interfaces [25] for providing variable levels of immersion could offer a path to overcome this by providing a context- and situation-dependent interaction paradigm. Furthermore, this integration could reduce challenges in collaborative SA acquisition through operator-centric presentation of information tailored to different levels of immersion and control, even in asynchronous teleoperations [24]. However, previous work has found that establishing group and workspace awareness among a team that simultaneously uses different levels of immersion and different display technologies is not trivial [25]. In some cases, teams tried to strictly avoid different immersion levels, resulting in inferior task performance. Future research in HCI and AR/VR will need to identify typical barriers to more efficient use of variable levels of immersion and overcome them using innovative designs.

Finally, our vision of delegating formerly human tasks to autonomous systems or conversing with a robotic system in natural language raises important questions, not only about technological feasibility but also psychological effects. Adverse effects of increased automation could include overtrust [22] and generally weaker supervision of systems. Also, human operators of telerobotic systems in space exploration are highly trained, skilled, and experienced professionals. Therefore, "natural" communication with a robot that reduces human task load but also human control could interfere with a team's basic psychological needs such as competence, i.e., the experience of effectiveness and mastery, and autonomy, i.e., the experience of volition and willingness, as was examined in previous work on supporting experienced seafarers with decision support systems for energy-efficient navigation [28].

5 Conclusion

We have introduced MIDA-VIC, a novel control paradigm for collaborative robotic teleoperation in space exploration. MIDA-VIC aims to address mixed-initiative dynamic autonomy settings with variable levels of immersion and control. By leveraging advances in HCI, HRI, AR/VR, and AI, MIDA-VIC enables human operators and robotic systems to flexibly adapt their collaboration modes to the requirements of specific tasks and operational constraints. Our conceptual framework allows for seamless transitions between immersive and non-immersive interfaces, as well as between manual, shared, and autonomous control. The goal is to enable mission teams to operate more effectively across varying task phases and technical challenges. MIDA-VIC supports diverse roles within teleoperation teams, considers the requirements and constraints of autonomous agents, and addresses the necessity of user- and robot-driven initiative. By supporting multiple interaction approaches in parallel and by enabling dynamic adjustments in both immersion and control, MIDA-VIC aims to provide the conceptual foundation for more responsive and intuitive teleoperation systems. We anticipate that the introduced paradigm has the potential to have broad implications not only for space exploration but also for other domains of remote robotic operation where human-robot collaboration is essential under complex and uncertain conditions. Future research should further investigate the design space of interaction modalities, the cognitive and operational impact of dynamic control, and the potential of LLMs and AI agents in enabling more natural human-robot interactions. MIDA-VIC offers a framework for exploring these directions to guide the development of next-generation collaborative systems.

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