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A Simulated Air Revitalization Task to Investigate Remote Operator Human-Autonomy Teaming With Communication Latency

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Future crewed missions to deep space will involve communication latency that makes Earth-based mission control infeasible. Autonomous systems may be able to remedy some of the challenges presented by this lack of real-time mission control. While communication latency's impact on human-human teaming has been studied, less understood is how latency impacts humans in supervisory control roles as they work with autonomous systems. We have developed a human-autonomy teaming task in which experiment participants act as remote operators communicating with an autonomous system onboard a deep space habitat with a simulated 10-second round-trip communication delay. This magnitude of communication delay is understudied but could be encountered on future lunar missions utilizing Gateway, or on deep space missions as approaching crews communicate with autonomous systems onboard distant habitats. Such autonomous systems will likely have a high level of autonomy as they maintain habitats during periods of dormancy, operating independent of Earth-based control. Motivated by this future scenario, the simulated autonomous system in our task can have a high level of autonomy as it maintains simulated air revitalization systems onboard the habitat (CO_2 removal, O_2 generation, trace contaminant removal), consulting with the remote human operator only when issues arise. This paper presents the motivation for our task, a discussion of previous work investigating human-autonomy teaming and communication latency, a description of the task's design and operation, and brief examples of past use and future work.

Nomenclature

CO_2	=	carbon dioxide
ISS	=	International Space Station
HITL	=	human-in-the-loop
HOTL	=	human-on-the-loop
ECLSS	=	environmental control and life support system
O_2	=	oxygen
CO	=	carbon monoxide
NH_3	=	ammonia
TC	=	trace contaminant

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I. Introduction

AUTONOMOUS systems show promise as teammates for human operators in the safety-critical and performance-critical environments of the future.[1] Autonomous systems are particularly suited as teammates for crewed deep space exploration missions, which will require human crews to be highly self-reliant and independent of Earth.[2–4] Adaptive autonomous systems, which can modify their own behavior in response to triggers like an operator's cognitive states, a task, or an environment, have been proposed as flexible teammates for working with humans.[2,5,6] By adapting to keep human operators working at their best, such autonomous systems may be able to enhance performance in space exploration where high levels safety and performance are demanded.[2,7,8] Early research into adaptive autonomous systems' impacts on human-autonomy teams emphasized mental workload and task performance, with adaptive task allocation between human operators and automated systems in manual control scenarios (e.g., manufacturing plant operation).[9–11] While the performance benefits found in this early research motivate adaptive autonomous system development, deep space exploration contexts present a number of challenges to adaptive autonomous systems that were not addressed in early research. For example, while autonomous systems may be able to adapt to known tasks or known performance targets in controlled environments on Earth, exploration contexts, such as deep space, lack known tasks or performance targets as human operators encounter novel environments. Understanding the demands of a deep space exploration environment on a human-autonomy team and investigating how such teams operate is necessary before adaptive autonomous systems can be utilized this environment.

II. Communication Latency and Supervisory Control

The communication delays involved with long-duration crewed missions to deep space are an obstacle to human operators. Artificially introduced communication delays of 100 seconds round trip between astronauts on the International Space Station (ISS) and ground controllers have been shown to affect performance and astronaut mood negatively.[12] Human-human communication strategies put in place to work around communication delays can reduce situation awareness or increase workload even for delays as short as five seconds round trip that would be present for Moon missions.[13,14] Even longer delays in communication on the order of ten minutes round trip between human-human teams have been shown to negatively affect spaceflight-relevant repair tasks even with some automation.[15] These long communication delays and the obstacles they present to crews make intensive Earth-based mission control (as is currently used for ISS operations) infeasible for deep space exploration missions. However, autonomous systems included as part of a deep space habitat or as part of a crew's spacecraft may be able to supplement the human crew and make up some of the deficit left by a lack of Earth-based mission control.[2–4]

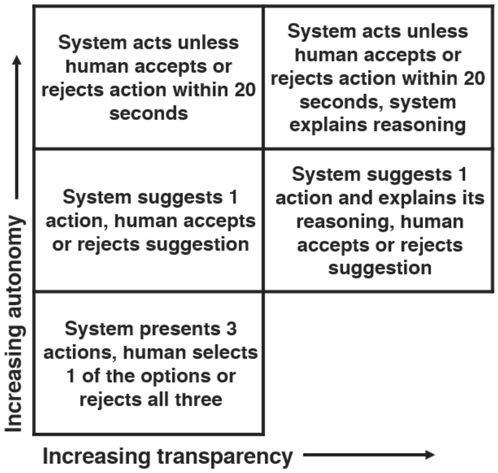
All the previously discussed research into latency's effect on astronaut performance investigated human-human communication when automation played no role or was not central to communication. Yet, how humans react to communications with autonomous systems may be different than or exacerbate some of the issues already seen in delayed human-human communications. Furthermore, there has been limited research into modest communication delays on the order of five to ten seconds round trip, and previous research on the effect of communication delays for spacecraft operations and emergencies did not investigate delays of that magnitude.[16] However, communication delays of this duration (five to ten seconds) could occur in future missions. For example, spacecraft exploring the Moon communicating with Earth-based support through a relay network will encounter elements of latency beyond signal travel time.[14,17] In addition, delays on the order of five to ten seconds could also occur in spaceflight far from Earth when a crewmember and an autonomous system are not co-located (e.g., an astronaut on transit vehicle far from an autonomous system maintaining a habitat). Further research into communication latency's effect on communications between a human and an autonomous system is needed.

The effect of direct teleoperation control modes on human operator workload and performance are relatively well understood by the community and are common to long time delay operations with NASA.[18–20] However, it will be undesirable to have human crews on future deep space habitats taking direct control of most habitat systems as crew time will be especially in demand. Thus, the "human-in-the-loop" (HITL) human-autonomy teaming paradigm that is the current norm on Earth and for space operations (either co-located or teleoperation) and is relatively well understood (e.g., [21,22]) will be less relevant to deep space exploration. Modes of operation in which humans take on a supervisory role as a remote operator monitoring an autonomous system in spaceflight (whether in real-world operations or in a simulation in a laboratory setting) are less understood by the research community. However, as astronaut crews on deep space missions will be without Earth-based support, those crews will largely operate in this "human-on-the-loop" (HOTL) mode with autonomous systems. This serves as a gap in human-autonomy teaming research which is impeding for deep space missions.

III. Air Revitalization Task

To investigate human-autonomy teaming for remote operators in a supervisory control role, we created a simulated air revitalization task in which experiment participants interact with a simulated autonomous system to maintain a deep space habitat's cabin atmosphere. Our task draws from the similar motivation as previously developed experiment tasks considering supervisory fault management for an ECLSS system.[23,24] However, our task makes use of a control paradigm where the operator is further "out of the loop" and in which the autonomous system has an even higher level of autonomy than in previous research. Elements of the task are described in further detail in the following sections. During the task, the autonomous system notifies the participant about events that cause cabin atmosphere parameters to fall outside of nominal bounds and provides suggested courses of action that the participant may accept or reject; the participant may not control any air revitalization systems directly. Once a participant selects a course of action, there is a 10 second delay in their being enacted on the participant's screen. The software used to create and run this task was written in Python using PyQt5 bindings[25] for the Qt 5 GUI framework[26] and can be found at https://osf.io/txdn2/.

A. Autonomous System, Events, and Message Panel

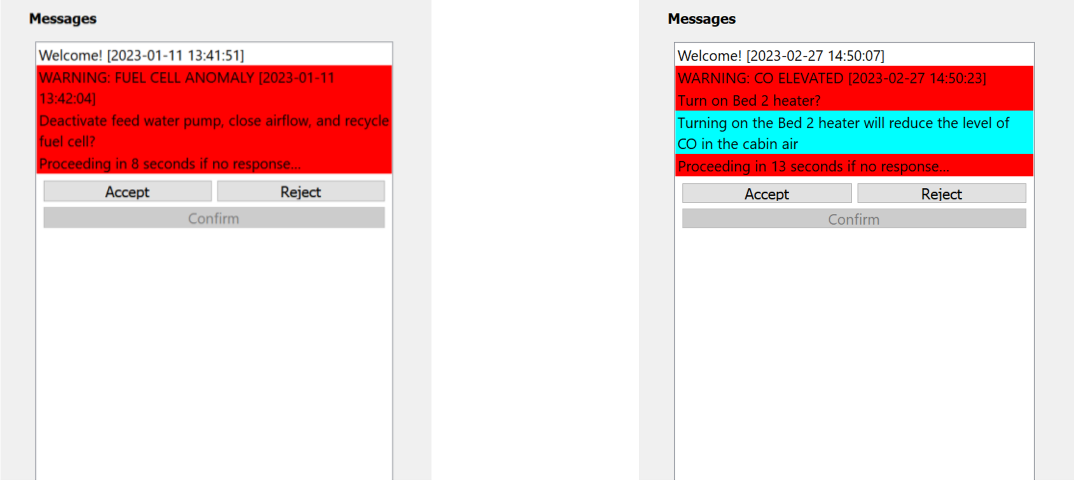


System acts unless human accepts or rejects action within 20 seconds	System acts unless human accepts or rejects action within 20 seconds, system explains reasoning
System suggests 1 action, human accepts or rejects suggestion	System suggests 1 action and explains its reasoning, human accepts or rejects suggestion
System presents 3 actions, human selects 1 of the options or rejects all three	

Figure 1. Modes of autonomous system operation.

Multiple modes of autonomous system operation were implemented into the task to enable experiments that address the previously outlined research gaps. Modes of operation for the autonomous system (outlined in Figure 1) were selected to correspond to roughly mid-levels of automation on Sheridan and Verplank's "Levels of Automation of Decision and Action Selection" scale, which specify the human cannot completely act without the autonomous system but the autonomous system cannot act without human input.[27,28] A mode of operation in which the system provides explanations for three suggested actions (the bottom right corner of the matrix) is not included in our task. While this could be implemented, it could lead to scenarios in which the explanations are confusing, complex, or contradictory to participants.

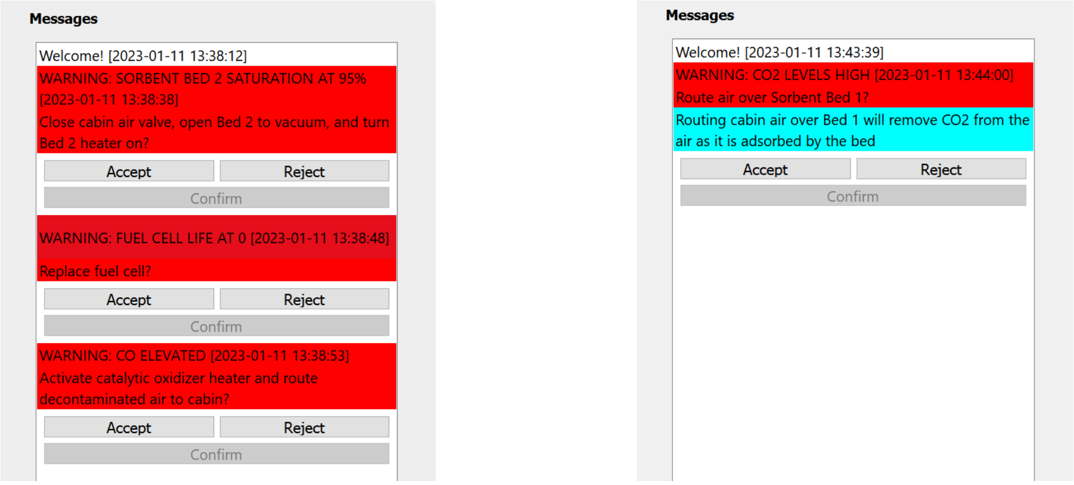
Previous research utilizing a similar ECLSS-relevant task considered different levels of autonomy corresponding to the scale as well, however the modes utilized in that work were generally of lower autonomy (e.g., still required the human to manually operate) than in this work.[29] The autonomous system in this work is entirely simulated and there is no logic driving or decision-making by the system; events are scripted in that the same warning messages are printed for a given event. However, each participant experiences trials in a random order that is generated when the task is first loaded, and so participants do not experience the same order of events. Additionally, on randomly selected trials that are different for each participant, the autonomous system can suggest erroneous courses of action at a rate specified by experimenters. Currently, this rate is set to 4 trials out of every 15. From the participant's perspective, this mimics a real-world scenario where occasionally the autonomous system functions imperfectly. Due to the random distribution of autonomous system reliability and autonomous system mode across trials, participants can experience completely different interactions with the autonomous system despite the scripted nature of events. Events are scripted to appear at given times during a trial. However, to avoid the confound of having an event occur while a participant is monitoring the associated portion of the task, events are defined to occur only when participants are not viewing the tab relevant to the event; in those cases, the events appear 2 seconds after the participant last viewed the relevant tab. On a given trial, up to 3 different events may occur, with each event being relevant to a different air revitalization subsystem (either carbon dioxide removal, oxygen generation, or trace contaminant control; see Sections III B, C, and D respectively). If participants are unsuccessful in remedying a given event (i.e., if they do not select the course of action that resolves the issue), it is presented to the participants again after 20 seconds as the alarm persists. Examples of event messages from the autonomous system are shown in Figure 2.



Welcome! [2023-01-11 13:41:51]
WARNING: FUEL CELL ANOMALY [2023-01-11 13:42:04]
Deactivate feed water pump, close airflow, and recycle fuel cell?
Proceeding in 8 seconds if no response...

Welcome! [2023-02-27 14:50:07]
WARNING: CO ELEVATED [2023-02-27 14:50:23]
Turn on Bed 2 heater?
Turning on the Bed 2 heater will reduce the level of CO in the cabin air
Proceeding in 13 seconds if no response...

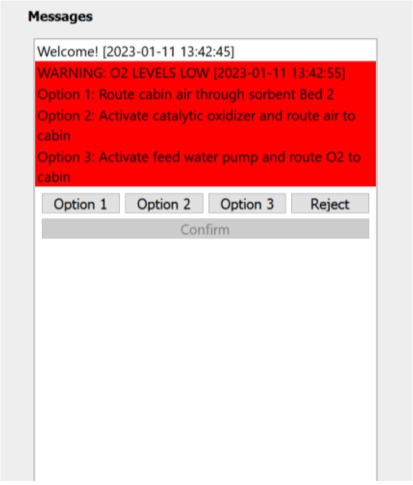
a) System acts unless human overrides **b) System gives explanation and acts unless human overrides**



Welcome! [2023-01-11 13:38:12]
WARNING: SORBENT BED 2 SATURATION AT 95% [2023-01-11 13:38:38]
Close cabin air valve, open Bed 2 to vacuum, and turn Bed 2 heater on?
WARNING: FUEL CELL LIFE AT 0 [2023-01-11 13:38:48]
Replace fuel cell?
WARNING: CO ELEVATED [2023-01-11 13:38:53]
Activate catalytic oxidizer heater and route decontaminated air to cabin?

Welcome! [2023-01-11 13:43:39]
WARNING: CO2 LEVELS HIGH [2023-01-11 13:44:00]
Route air over Sorbent Bed 1?
Routing cabin air over Bed 1 will remove CO2 from the air as it is adsorbed by the bed

c) Three events, system provides one option **d) System provides one option and an explanation**



Welcome! [2023-01-11 13:42:45]
WARNING: O2 LEVELS LOW [2023-01-11 13:42:55]
Option 1: Route cabin air through sorbent Bed 2
Option 2: Activate catalytic oxidizer and route air to cabin
Option 3: Activate feed water pump and route O2 to cabin

e) System provides three options

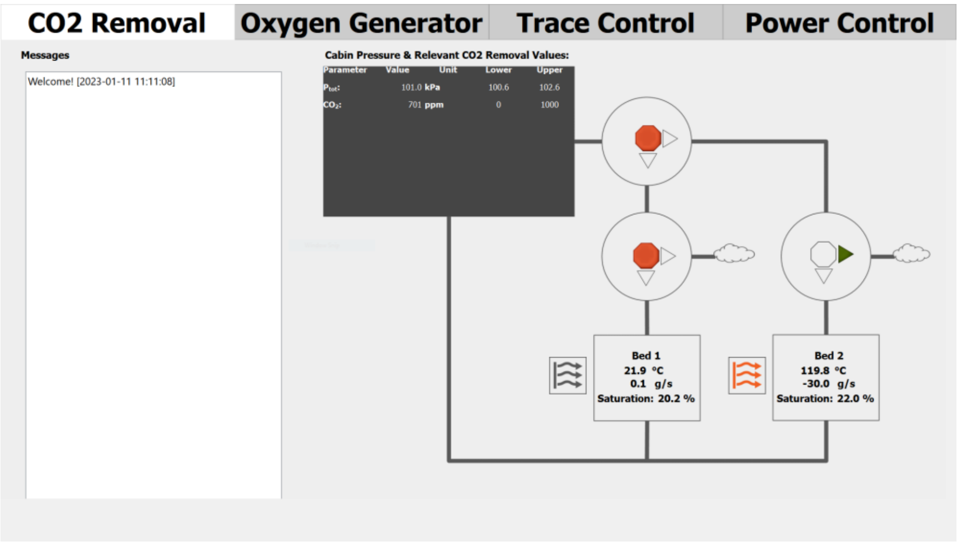
Figure 2. Examples of event messages from the autonomous system in each mode of operation.

The message panel is where participants are notified of events that require their attention during trials. The panel is persistent between all different tabs of the interface and is how participants communicate with the simulated autonomous system. Critically, during experiments, participants are *unable to control valves and system controls directly*; they must wait for the autonomous system to offer a relevant course of action and then select that course of action. The autonomous system then enacts the selected course of action. The delay in communication between the participant and the space habitat is reflected in the changing colors and states of on-screen indicators and buttons – before indicating that a button has been activated or deactivated, it will flash yellow for 5 seconds (reflecting the command in transit to the space habitat), and then turn a solid yellow color for 5 seconds (reflecting that the command has been assumed enacted on the space habitat, but has yet to be confirmed) before turning its ultimate state and the cabin air parameter data begins to reflect the change on the operator's display.

Depending on the mode of operation of the autonomous system, the options available to the participant in the message panel for selecting a course of action change (either buttons for three options that are described in the event message along with a reject button, or buttons to accept or reject the suggested course of action). When participants reject a given suggestion or set of suggestions, the message is printed again to the message panel after 20 seconds have elapsed. The text of the warning message is the same, however the suggested course of action provided to the participant may be the same or may be different depending on the autonomous system's mode of operation. In cases where the system is suggesting incorrect courses of action, the incorrect options provided to a participant have their order randomized.

B. CO_2 Removal

The two-bed CO_2 removal system simulated in the task is loosely based upon a sorbent bed CO_2 removal system used as an environmental control and life support system (ECLSS) testbed at the University of Colorado – Boulder.[30] Valves and sorbent beds are presented on the CO_2 Removal tab in the task interface in a way that reflects the actual system's operation, as shown in Figure 3. Cabin air parameters relevant to CO_2 removal such as total cabin pressure and CO_2 levels (in parts per million) are indicated in the gray box in the upper left part of the tab. Nominal values for CO_2 fall below the limit of 1000 ppm. Valve closures and valve directions are all indicated with red (closed) or green (open flow) colored icons on the display, while sorbent bed heaters turn orange when activated. Sorbent bed symbols also include information like bed temperature, mass flow rate over the bed, and bed saturation. While these parameters do not reflect data that is available for a real-world CO_2 removal system that utilizes sorbent beds, it provides experiment participants with information such that they do not need to be expert ECLSS operators to understand and act during the task. Additionally, the rates of adsorption and desorption simulated for this subsystem are not based on empirical equations that describe the physical processes. However, the changes in CO_2 levels and rate of adsorption/desorption of the sorbent beds were found to be plausible to participants during pilot testing of the interface. Furthermore, the rates produce the desired events on the timescale of approximately minute-long experiment trials (e.g., adsorbing 100 ppm CO_2 from the cabin air with an unheated, unsaturated bed takes approximately 8 s).



Welcome! [2023-01-11 11:11:08]

Cabin Pressure & Relevant CO2 Removal Values:

Parameter	Value	Unit	Lower	Upper
P_{tot}:	101.0	kPa	100.6	102.6
CO_2:	701	ppm	0	1000

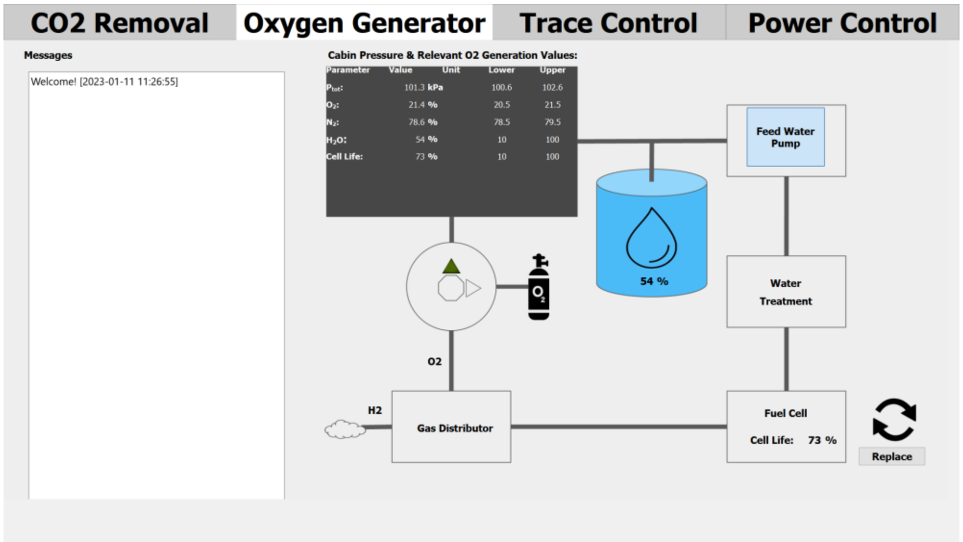
Bed 1
21.9 °C
0.1 g/s
Saturation: 20.2 %

Bed 2
119.8 °C
-30.0 g/s
Saturation: 22.0 %

Figure 3. CO_2 Removal tab indicating that one sorbent bed (Bed 2) is being heated and desorbing to vacuum.

C. Oxygen Generator

In the task, oxygen is generated through a simulated electrolysis system, which is presented to participants on the Oxygen Generator tab shown in Figure 4. Each trial of the task begins with a set amount of water that participants can feed into a fuel cell to perform electrolysis and produce oxygen that can either be fed into the cabin atmosphere or into a "storage tank." Hydrogen produced by the electrolysis is vented to vacuum. Once during a trial, the fuel cell used for electrolysis can be replaced with a new fuel cell if its life drops too low and the autonomous system sends a message to the participant indicating so. The cabin air parameters listed in the grey box shown in the upper left of the panel are mostly different than those shown in the grey box for CO_2 removal (see Figure 3) and are relevant to oxygen generation: total cabin pressure, oxygen level, nitrogen level, water remaining in the storage tank for electrolysis, and fuel cell life remaining. Nominal values of O_2 fall within the lower bound of 20.5% and the upper bound of 21.5% atmosphere composition. As with the CO_2 removal system, the rate of change of cabin air parameters when electrolysis is activated in the task is not based on high-fidelity models of the processes but still produces plausible dynamics.



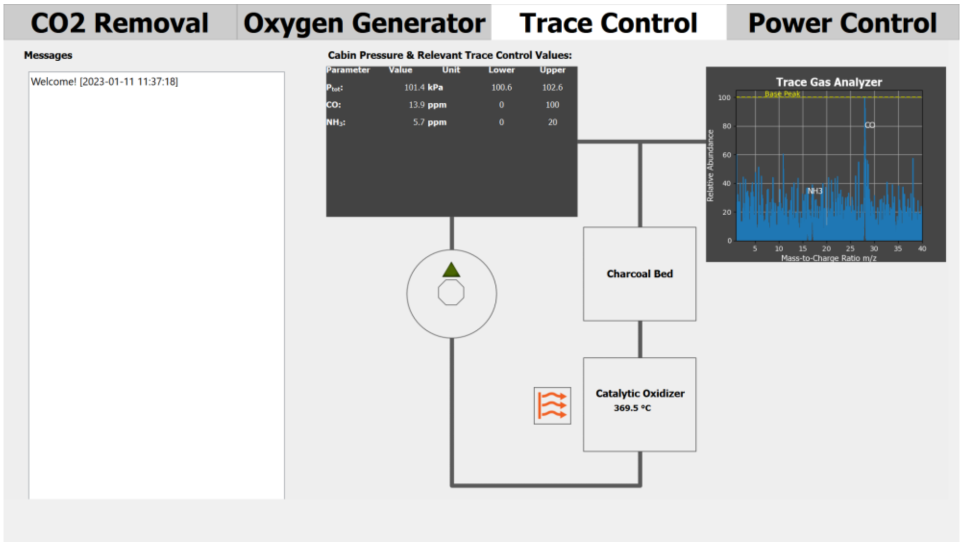
Welcome! [2023-01-11 11:26:55]

Parameter	Value	Unit	Lower	Upper
P_{tot}:	101.3	kPa	100.6	102.6
O_2:	21.4	%	20.5	21.5
N_2:	78.6	%	78.5	79.5
H_2O:	54	%	10	100
Cell Life:	73	%	10	100

Figure 4. Oxygen Generator tab showing electrolysis activated and oxygen flowing to the cabin.

D. Trace Contaminant Control

Participants are tasked with monitoring two trace contaminants (TCs), ammonia (NH_3) and carbon monoxide (CO), and removing them if their levels exceed nominal limits (100 ppm for CO and 20 ppm for NH_3). When TCs exceed their nominal limits, the autonomous system sends a warning message in the message panel. The Trace Control tab of the task is shown in Figure 5. To remove TCs, a valve can be opened to route cabin air over two removal systems: a charcoal bed to remove NH_3, and a catalytic oxidizer to remove CO once heated. In addition to the grey box which shows cabin air parameters relevant to the TC control (total pressure, ppm of CO, and ppm of NH_3), participants are provided with a simulated "Trace Gas Analyzer" (mass spectrometer) which provides a quick reference for the relative concentrations of TCs in addition to the information provided in the grey box with cabin air parameters. As with the other two air revitalization subsystems, the rates of change of TC levels are not based on high-fidelity models of the processes but still produce plausible dynamics.



Messages

Welcome! [2023-01-11 11:37:18]

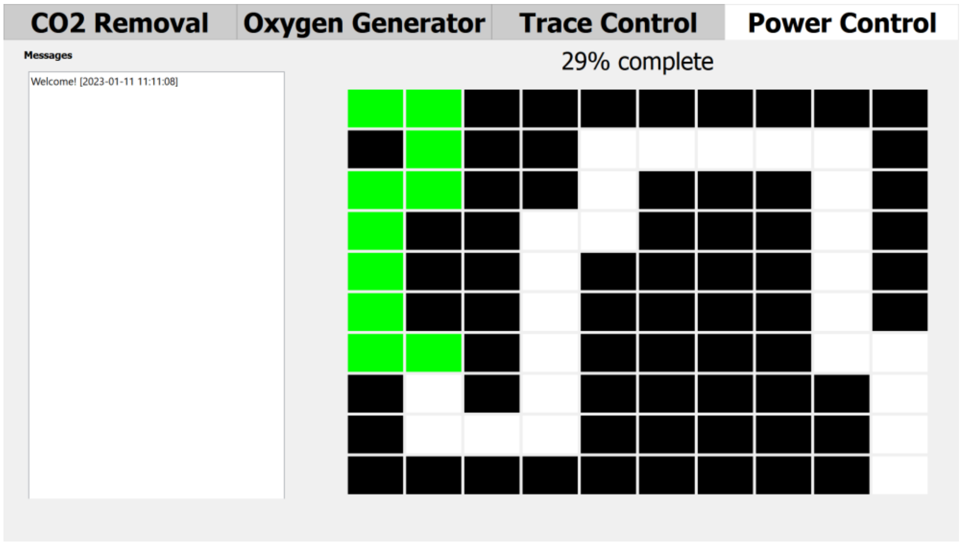
Cabin Pressure & Relevant Trace Control Values:

Parameter	Value	Unit	Lower	Upper
P_{tot}:	101.4	kPa	100.6	102.6
CO:	13.9	ppm	0	100
NH_3:	5.7	ppm	0	20

Figure 5. Trace Contaminant Control tab indicating the catalytic oxidizer is being heated and contaminants are being removed from air that is then routed back to the cabin atmosphere.

E. Power Control Secondary Task

To facilitate human factors studies, an embedded secondary task was included in the interface as a way to query spare mental capacity of participants while they complete the air revitalization task.[31–35] Participants are told that the power control system onboard the space habitat can "learn" more efficient "power routings" from the participants if they complete the secondary task and route power (complete a maze with their cursor) successfully. If participants switch tabs while completing a routing their progress is saved. However, if participants mistakenly drag their cursor an area outside of the routing (the black boxes shown in Figure 6), their progress is reset. After participants complete a routing, they can switch away from the Power Control tab, and upon switching back to the Power Control tab a new routing will be available for them to complete.



Messages

Welcome! [2023-01-11 11:11:08]

29% complete

Figure 6. Power Control tab showing progress on the secondary "power routing" task.

IV. Features for Human Experiment Protocols

In addition to the components of the air revitalization task described in Section III, we also make use of the following features in human experiments to keep participants engaged in the task and facilitate investigations of participants' interactions with the simulated autonomous system.

A. Pre-Experiment Training

To ensure that participants will be able to identify correct courses of action to remedy events that arise while they complete our task, we have developed a briefing presentation that participants read before completing our task. The presentation summarizes ECLSS concepts (such as the need to remove carbon dioxide from a crewed spacecraft cabin atmosphere) and provides specific instructions for completing each element of our task. Experimenters are available while participants read the presentation to provide clarification and answer any questions participants have. At the end of the training presentation, participants complete a brief quiz to check their comprehension and ensure that they remember critical parts of the training. The training presentation can be found along with a downloadable version of our task at https://osf.io/txdn2/.

B. Incentives and Penalties

Providing participants with more stakes in an experiment task may lead to more genuine human-autonomy teaming, as humans take on vulnerability in relying on the autonomous system when an error made by the system could cost them money.[36,37] Motivated by this desire to have more complex, realistic human-autonomy teaming, the task has a built-in payment reward system which incentivizes participants to perform well. Participants are rewarded for every second that each cabin air parameter is kept within nominal bounds listed on their display, through effective collaboration with the autonomous system. They are penalized for every second that cabin air parameters are outside of the nominal bounds. Notably, when events occur and the autonomous system suggests erroneous courses of action, it may be difficult or even impossible to maintain cabin air parameters within nominal bounds. This replicates a genuine human-autonomy teaming paradigm with co-dependence for success. Furthermore, participants can earn a small (relative to the reward for maintaining the cabin air) bonus for completing routings on the Power Control tab, motivating participants to perform the embedded secondary task when their spare mental capacity allows.

C. Trial Ends

Task trials last between 50 and 95 seconds, with events occurring as participants work with the autonomous system to maintain the cabin atmosphere, until at a randomly defined instant the trial suddenly ends by "freezing" (i.e., the task screen disappears abruptly and the task ends). When a trial freezes, participants are first presented with digital questionnaires in a random order that they complete using the computer mouse to rate their trust in the autonomous system,[38] mental workload,[39] and situation awareness.[40,41] Once these questionnaires are submitted, participants are shown a summary of their rewards/penalties for the just completed trial. Additionally, to let participants know the outcomes of their actions despite trials ending without participants being able to see the resulting cabin air parameters, participants are presented with one of two messages: either "The actions your team took to address events will ensure nominal habitat atmosphere and that habitat systems function properly" shown on a green background or "The actions your team took to address events will NOT ensure nominal habitat atmosphere and that habitat systems function properly" shown on a red background. On trials where the autonomous system does not provide a course of action to participants that would remedy the events of the trial, participants are still shown the message on the red background (the negative message) even though there was no action they could have taken to remedy the events. In this way, the participant and the autonomous system are treated as a true "team" in that their reward requires both team members to work successfully, and that the team cannot earn the reward if one of the team members makes a mistake.

V. Examples of Use

Here we describe a previous experiment that utilized our task as an example of its use in human research. We also describe two proposed studies that could be conducted using our task to illustrate its flexibility for research objectives.

A. Investigating the Autonomous System's Effect on Cognitive States

To investigate how each autonomous system mode of operation affected participant cognitive states (trust, mental workload, and situation awareness), we conducted an experiment in which participants experienced three trials each of the five autonomous modes in a random order. On 11 trials out of the 15 the system gave correct suggestions for actions to take. As participants worked with the autonomous system to maintain the cabin atmosphere (and earn rewards) in the presence of a 10-second round-trip communication delay, we collected data about the on-screen actions participant took, what tabs they viewed, and what they were looking at on the screen using eye tracking glasses as shown in Figure 7. After each trial of the experiment, participants completed three questionnaires to rate their trust,[38] mental workload,[39] and situation awareness[40,41] as they were at the instant the trial ended. Figure 8 shows histograms for each questionnaire demonstrating that a range of scores was obtained for each cognitive state across all participants' trials. Using questionnaire data, data obtained from the task, and data obtained from physiological sensors worn by participants, statistical analyses were conducted to determine how different actions, events, and modes of autonomous system operation affected the questionnaire responses provided by participants.

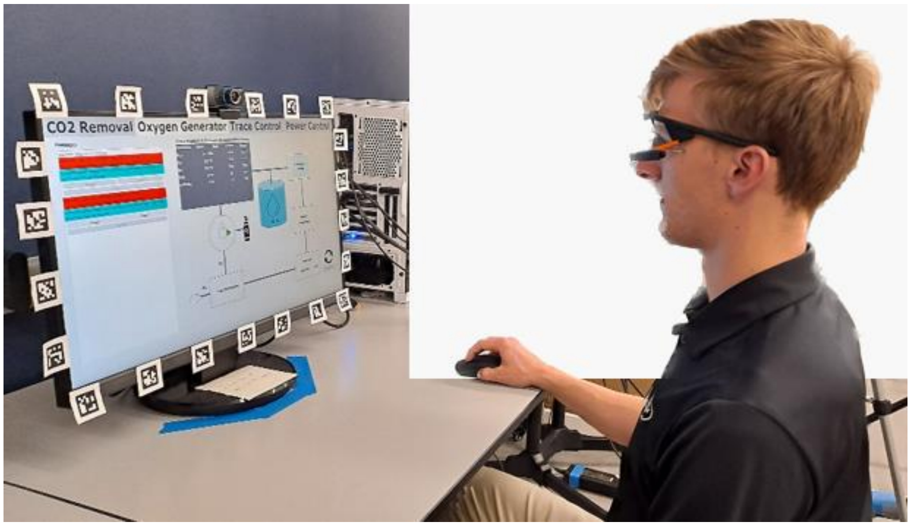


Figure 7. Example of participant (person shown is part of the research team) seated with eye tracking glasses while performing the task.

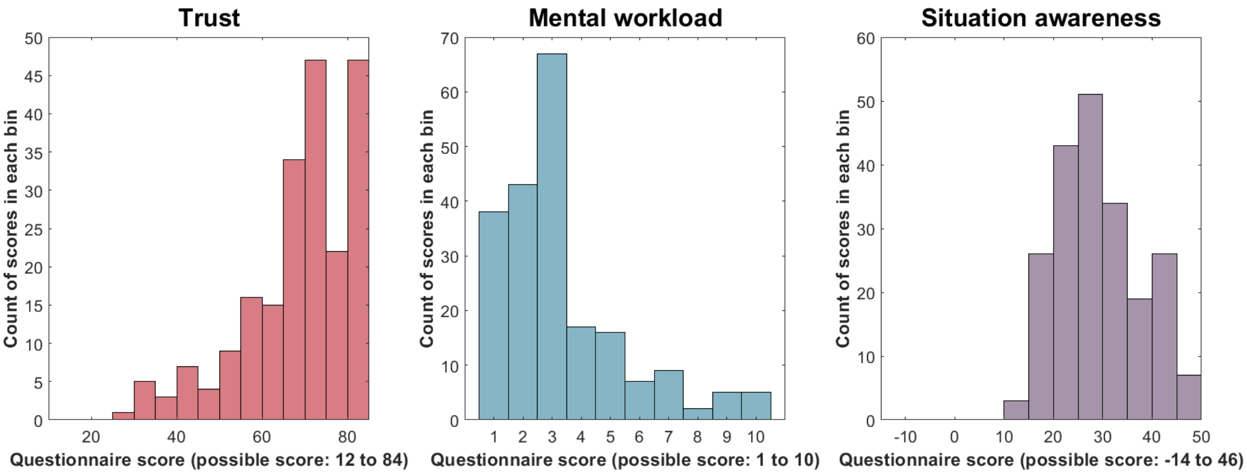
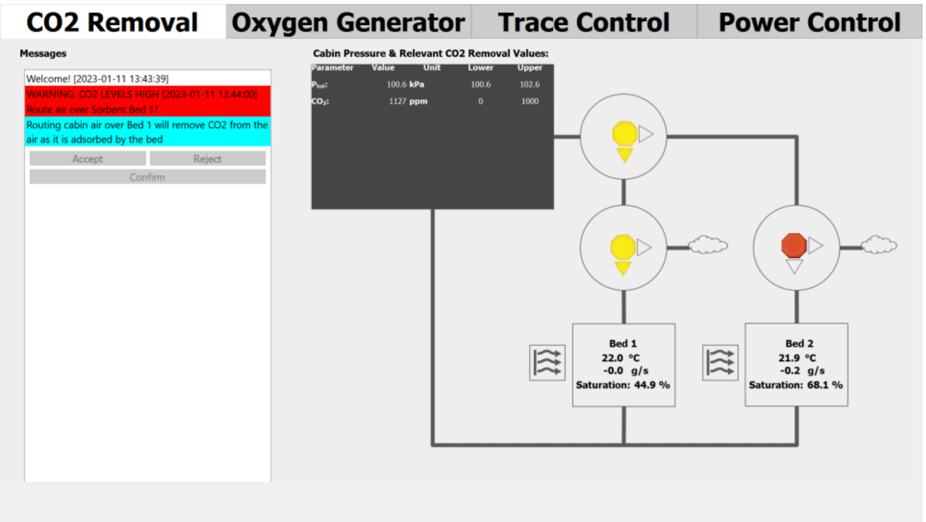


Figure 8. Histograms of trust, mental workload, and situation awareness questionnaire ratings by participants at the moment their trial froze (14 participants, 15 trials each). For all questionnaires, higher scores reflect higher levels of the cognitive state being measured.

B. Proposed Experiment to Study Communication Delay

A range of round-trip communication delays could be encountered by crews on future deep space exploration missions during their transit to a deep space habitat, as communication delay is proportional to distance. While the current round-trip communication delay implemented into the task is 10 seconds, the delay magnitude can be manipulated as an independent variable in an experiment to investigate how different communication delays impact human cognitive states or human-autonomy team interactions. As shown in Figure 9 and described previously, delays in communication between the participant and the deep space habitat are reflected in the color and flashing of valve and heater indicators on the task display, as well as the delay in cabin air parameters updating their values once a relevant action has been taken. An experiment could investigate how a given participant reacts to the same behavior by an autonomous system in the face of different magnitudes of communication delay (e.g., if a system offers erroneous suggestions, does a longer delay decrease participant trust in the system more than a shorter delay?) This would include assessing the control condition in which there is no simulated time delay between the participant and the autonomous system and actions are instantly received and enacted by the system.



Welcome! [2023-01-11 13:43:39]

WARNING: CO2 LEVELS HIGH [2023-01-11 13:44:00]
Route air over Sorbent Bed 1?

Routing cabin air over Bed 1 will remove CO2 from the air as it is adsorbed by the bed

Cabin Pressure & Relevant CO2 Removal Values:

Parameter	Value	Unit	Lower	Upper
P_{tot}:	100.6	kPa	100.6	102.6
CO_2:	1127	ppm	0	1000

Bed 1
22.0 °C
-0.0 g/s
Saturation: 44.9 %

Bed 2
21.9 °C
-0.2 g/s
Saturation: 68.1 %

Figure 9. Button states reflecting communication delay, turning yellow before indicating their final states.

C. Proposed Technology Demonstrations

Events, cabin air parameter states, options, and explanations offered by the autonomous system are scripted by default in the current task setup. However, the flexibility of the software used to create the task allows for experiment conductors to modify the task for use in demonstration of new technologies, such as:

- For greater realism or an emphasis on high-fidelity cabin atmosphere revitalization processes and timescales, the data provided to the simulation could be drawn from a real-world testbed or from a model of an operational ECLSS system, rather than the simulated data shown to participants in the current task setup.
- The courses of actions suggested by the autonomous system could be generated using a real (not simulated) autonomous system (i.e., employing logic based upon simulated sensor data with various sources of uncertainty). Furthermore, the explanations offered for a given event could be created using a logic for causal explanations which has already been demonstrated for the real ECLSS testbed upon which our task's CO_2 removal is based.[42] These demonstrations would provide more realistic autonomous system output to participants and could be used in experiments to investigate how real-world explanations would affect human operators' cognitive states or performance on the task.

VI. Conclusion

As human crews venture farther into deep space on exploration missions, the communication latency between Earth and their spacecraft necessitates greater autonomous system integration into deep space habitats. Understanding how communication delay and an autonomous system's level of autonomy affect human-autonomy teams is critical to enable safe, high-performing human-autonomy teams in spaceflight. To facilitate better understanding of how these future systems and human operators work together, we have created a flexible task for experiments that study ECLSS-relevant human-autonomy teaming in the face of communication delays. Future work leveraging this task in experiments or technology demonstrations will inform how adaptive autonomous systems can best support human operators during the deep space exploration missions of the future.

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