TeleLayering: Teleoperated Construction 3D Printing Using Multimodal Feedback for Extraterrestrial and Terrestrial Construction

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***Abstract* - In this paper, we propose a teleoperated construction 3D printing technology, called TeleLayering, for planetary and terrestrial applications. The TeleLayering technology is enabled by effective multimodal control and monitoring systems and enhanced construction 3D printing robots to build or repair a variety of structures in extreme environments without the need for human presence on the jobsite. This paper presents a general description, main technical requirements, implementation challenges, and applications of this technology.**

I. Introduction

Reportedly, in the United States alone, over 1100 construction worker fatalities happen each year [1]. Removing human workers from the construction sites can prevent the frequent injuries and fatalities, and can minimize human exposure to dust and other hazards typically present at construction sites. Teleoperation of construction machinery is one approach to achieving this goal. Teleoperation, in general, enables interactions with robotic manipulators remotely, extending human manipulation capabilities to far-off locations to execute complex tasks while avoiding unsafe environments [2]. Teleoperation enables human-robot teams to complete challenging tasks, where robots can be used for labor-intensive, dangerous, and repetitive tasks, while humans with their unmatched cognitive capabilities can engage in supervisory control, such as real-time process modifications due to contingencies. The first bilateral teleoperation system was developed in the 1940s by researchers at the Argonne National Laboratory for remote handling of radioactive materials [2]. The first mechanisms were mechanically coupled, with the slave manipulator mimicking the master motions. The first electrically-coupled master-slave teleoperation system was developed in the 1950s [2, 3]. Since then, a variety of wired and wireless telerobotics systems have been used for different applications such as surgery, underwater operations, maintenance, and space missions [4, 5]. Telerobots have been used in space as early as 1970. The Lunokhod 1 rover landed on the Moon in November 1970 and was followed by Lunokhod 2 in January 1973, both remotely operated from Earth [6, 7].

Teleoperation has the potential to significantly improve worker safety in different domains while offering other benefits. For example, Khoshnevis [8] proposed a teleoperated manufacturing paradigm for complex manufacturing tasks which cannot be fully automated and require human skills. The manufacturing industry can adopt this new approach to deal with pandemics and other challenges associated with crowded and congested working environments. In the construction industry, teleoperation has been previously used to remotely control heavy machinery for excavation, leveling, and demolition [9, 10]. Kita *et al.* [5], for example, developed and successfully tested a teleoperated underwater excavator, for seabed leveling controlled by a teleoperator on a ship. The developed system includes three major subsystems: underwater information representation, a seabed mapping module, and an easy-to-operate attachment for seabed leveling. In order to calculate and represent the posture of the excavator during underwater operations, the customized underwater excavator was equipped with a variety of sensors such as a gyroscope, a depth gauge, and an underwater acoustic positioning device [5]. These successful experimental efforts, as well as real-life applications of teleoperation in excavation, highlight the great potential of teleoperation for remote operation of construction machinery.

In this paper, we propose a telerobotic infrastructure construction 3D printing (C3DP) technology, called TeleLayering, for extreme environments. Currently the existing C3DP technologies on Earth rely heavily on the human presence on the job site. Manual inspection and process modifications are typically required to ensure the successful completion of the construction process.

Examples of typical manual process modifications during C3DP include nozzle height adjustments and printing speed and extrusion rate modifications. These manual modifications are commonly needed to prevent excessive layer deformations, surface defects, and collapse of freshly printed structures. TeleLayering, however, provides a solution for conditions where human presence on the jobsite is not safe or feasible. The teleoperated C3DP technology for extreme environments, as described in this paper, has not been previously implemented for either terrestrial or extraterrestrial applications. Therefore, the new requirements regarding system design and control schemes for extraterrestrial and terrestrial TeleLayering will be presented in the following sections.

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II. TeleLayering: Description and Technical Requirements

The TeleLayering technology includes four main components: (1) a specialized remotely controlled mobile C3DP robot equipped with onboard sensory, data processing, and control systems as well as a robotic gripper, (2) a bi-directional feedback and control interface which supports multiple control modes, (3) a wireless communication system, and (4) a human teleoperator. The specifications and technical details of each element depends on the application for which the TeleLayering system is designed. The general requirements and considerations for each component is discussed in the following paragraphs.

A **specialized C3DP robot** is one of the most important aspects of TeleLayering, which works in concert with the human teleoperator to complete the construction related tasks in the remote site. There are four main performance requirements for TeleLayering robots: (1) Navigation and operation in unstructured and unknown environments (robustness, reliability, and resilience), including fault and anomaly detection and mitigation; (2) Ability to collect critical process and environment data which could affect the construction process; (3) Ability for local data processing and control for automated completion of sub-tasks; (4) Ability to complete tasks beyond layer extrusion, such as pick-and-place operations.

A bi-directional multimodal **feedback and control interface** is another key component of a TeleLayering system, which realizes a continuous or intermittent information flow between the human operator and the remote robot. The first main requirement for a TeleLayering interface is to facilitate perception of the remote environment by the teleoperator, given the bandwidth and telecommunication limitations. Maintaining a balance between complexity and operability is the main challenge in design of a TeleLayering interface, since a wide range of parameters and data can be presented to the human teleoperator in various modalities (video, augmented reality, digital twin models, quantitative process parameters, etc.).

A related constraint is the bandwidth limitations that commonly limit the amount of real-time data that could be presented to the human teleoperator. With the ongoing advancements in telecommunications networks (e.g., 5G technology), this limitation will not be as significant in the future. Still, the amount of data presented to the teleoperator, and their modalities, need to be carefully determined. Presenting a large amount of data to the teleoperator can result in cognitive overload and fatigue, which in turn can severely impact the teleoperator's performance and decision-making ability [9, 12].

The second main technical requirement for a TeleLayering interface is to support multiple control modes, with the capability of switching between these modes during the operation. We envision a wide range of autonomy levels for TeleLayering. Specifically, we propose two operation modes, a shared autonomy mode and a supervisory control mode, which can be deployed in various scenarios, while some complex tasks may require transition between these operation modes. Table 1 summarizes the automation levels for several tasks involved in TeleLayering under the two proposed operation modes.

Shared autonomy (shared control) allows the teleoperator to directly guide the nozzle movements within the build envelope to construct different objects layer by layer without the need for a CAD model (on-demand construction) and to install reinforcement or other components during the construction process by directly controlling the robotic gripper. In this operation mode, process parameters such as extrusion rate or temperature are controlled automatically, or with minimal input from the user (such as "material type"). With supervisory control, however, much of the operation is autonomous, and the teleoperator only intervenes when it is necessary, to prevent process failure. This operation mode relies heavily on the advanced sensory systems and edge computing capabilities of the remote TeleLayering robot.

Various automated quality control techniques for conventional C3DP systems have been implemented and studied by researchers. Machine vision, 3D laser scanning, and extrusion monitoring using various inline sensory systems have been investigated [13, 14, 15]. For example, Kazemian *et al.* [16] designed and demonstrated an adaptive extrusion system based on machine vision for automated extrusion rate control during C3DP, using an embedded single-board computer. 2D and 3D vision systems, specifically, hold great promise as tools for non-contact measurements during TeleLayering and for feedback to the teleoperator to enable reliable remote control. In terms of overall productivity and operability, the supervisory TeleLayering mode is preferred. However, its implementation is technically more challenging and requires integration of advanced and reliable sensory and edge computing systems into the remote robotic system. Shared autonomy, on the other hand, is a more practical approach for scenarios requiring human dexterity and creativity, such as emergency construction.

Table 1. Various levels of autonomy with TeleLayering

	TeleLayering Operation Modes	
Task	**Shared Autonomy**	**Supervisory**
Robot Navigation	Direct Control, Guided or Automated	Automated
Nozzle Movements	Direct Control	Automated
Extrusion Parameter Selection	Guided or Automated	Automated
Pick-and-place Operations	Direct Control or Guided	Guided or Automated
Real-time Modifications (contingencies)	Direct Control or Guided	Direct Control or Guided

With respect to the **wireless communication system**, the general requirements are similar to other teleoperation systems: high bandwidth and low latency to allow a continuous bi-directional information flow and to reduce the chances of instabilities induced by time delays. Given a reliable and intelligent construction robot, high-latency TeleLayering also seems technically feasible in the future. However, low-latency TeleLayering is a more viable starting point. Implementation of low-latency TeleLayering systems can generate the necessary data (on the process failure modes and intervention strategies) to design TeleLayering systems with a higher degree of automation which can possibly be teleoperated over high-latency wireless networks.

The **human teleoperator** plays an important role in any telerobotic system, by perceiving the information from the remote site through the interface, and making decisions and sending commands to the remote robot accordingly [17]. Human factors, such as the cognitive capacity to interpret real-time data, and the impact of telecommunication latency levels on the teleoperator's performance, must also be considered during the design process. Examples of quantitative metrics for overall human-robot performance evaluation include task completion time, percentage of overall mission completed, or use of standard surveys to assess situational awareness and cognitive load [18, 19].

Finally, teleoperation functionality will significantly affect TeleLayering hardware design. While different robotic configurations have been used for C3DP in the past, considerations related to TeleLayering control schemes and the required autonomy will give rise to new design requirements. For example, which configurations- robot type and mobility platform- lend themselves more readily to the TeleLayering requirements in extreme environments?

III. Applications

TeleLayering systems can be designed for remote operation either with or without direct line-of-sight. The latter has a broader range of applications and is the main focus here. We discuss the applications of this technology in planetary and terrestrial construction, as well as some of the performance requirements in each domain.

A. *Extraterrestrial TeleLayering*

TeleLayering can be deployed for infrastructure construction, repair, and outfitting on the Moon and Mars. For planetary construction missions, requiring on-site presence of astronauts and assigning manual tasks to them during extraterrestrial construction is inefficient, unsafe, and costly. In addition, the inspection and process adjustments that are commonly done by human workers during C3DP on Earth, cannot be easily carried out by a suited astronaut, as extravehicular activity (EVA) suit systems typically encumber an astronaut's range of motion, reach, and field of view [7]. TeleLayering enables reliable operation of mobile C3DP robots on the planetary surfaces by astronauts who are not present on the job site but remotely monitor and control the process from an environmentally controlled command center. It also eliminates the need for prolonged EVA operations which expose astronauts to harmful radiation and contamination on planetary surfaces during construction. In addition, TeleLayering has great potential to be deployed in precursor missions for Lunar and Martian construction, in advance of crewed missions.

Developing fully autonomous planetary construction systems is highly desired by NASA and other space agencies. However, considering the extreme extraterrestrial conditions, the associated uncertainties, and lack of relevant data, fully autonomous construction does not seem viable in the near future. TeleLayering, on the other hand, can serve as a viable solution that can be used during upcoming Artemis missions and enable a gradual transition towards fully automated planetary construction. The implementation of the TeleLayering technology can result in valuable sensory and tele-control data from different operation modes, which can be used to design advanced control algorithms and augment the autonomy of C3DP robots over time, and ultimately enable fully autonomous planetary construction.

With respect to system design and implementation, planetary TeleLayering is significantly more challenging compared to terrestrial TeleLayering. Reliable and durable C3DP robots are required to navigate the rough Lunar and Martian terrains and successfully complete the assigned construction or repair tasks in an environment with a high degree of uncertainty. Considering the high costs and limited opportunities for maintenance and repair in planetary environments, these robots must be designed for a longer service life and a higher degree of robustness, compared to terrestrial robots.

Time delay (latency) is another major technical challenge in space telerobotics. In high-latency scenarios such as Mars Exploration Rovers (MERs) with tens of minutes of delay, command sequences are often intermittently uplinked to the robot by mission control. The robot then functions independently for long periods without communication with teleoperators at mission control [7]. As a starting point for technology development, low-latency TeleLayering seems to be more viable. For Lunar construction, the TeleLayering robots on the Moon can be controlled by the crew in the Lunar habitats or crew lander (over-the-horizon commanding), or from Earth-Moon libration point with round trip time latency of approximately 400 ms, or even possibly from the Earth. On Mars, TeleLayering robots can be controlled by human crew in nearby Martian habitats or from vehicles on orbit.

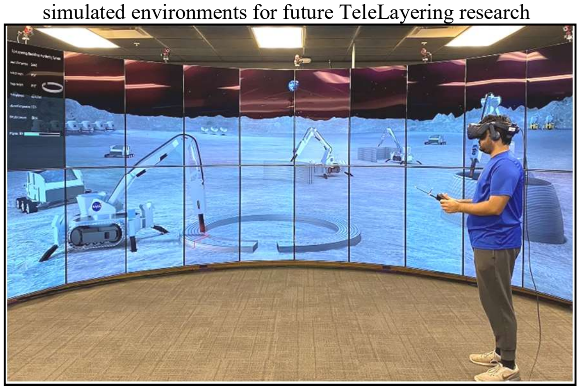
B. *Terrestrial TeleLayering*

On Earth, TeleLayering can be used for construction and repair of structures in extreme environments, such as the vicinity of active volcanoes, underwater, active war zones, or in areas with high radiation levels due to nuclear accidents. In the case of hazardous chemical leakage or nuclear accidents, TeleLayering robots can be used to construct temporary structures to confine the source of the hazard. In applications where a large number of structural elements and substructures are produced repeatedly (such as prefabrication factories), TeleLayering can improve the construction productivity and reduce the need for laborious manual activities by assigning humans to supervisory and telecontrol roles. By advancing the TeleLayering technology toward supervisory operation mode, it would be possible to assign one teleoperator to multiple remote robots, which will significantly improve the overall productivity.

IV. Challenges and Research Needs

One of the key aspects of TeleLayering technology is the control and monitoring interface, which provides the necessary situational awareness to the human teleoperator, and sends commands to the remote robot. The requirements for each operational mode must be studied during the design and implementation of a TeleLayering interface. For the shared autonomy operation mode, for example, the interface should be equipped with controllers for capturing the user's direct spatial inputs for nozzle movements. One possibility is using force and haptic feedback for direct control of nozzle movements within specified boundaries. Extensive research and systematic studies are needed to evaluate the efficiency of different control and feedback interface configurations, considering the relevant human factors. Virtual environments can be used for initial investigations on the performance of various systems and the teleoperator performance in simulated environments (Figure 1). Virtual environments can also be used for training teleoperators, especially in preparation for future space missions.

Figure 1: BIM CAVE facility at Louisiana State University – Using simulated environments for future TeleLayering research



Another area which needs extensive research is the TeleLayering robot design, as well as innovative material delivery systems which can support mobile TeleLayering robots. Depending on the specific application, TeleLayering robots should be able to complete multiple tasks in addition to large-scale 3D printing, including reinforcement installation, outfitting, coating, and pick-and-place tasks. Enhanced C3DP robots equipped with robotic grippers can be used to complete the majority of these tasks. Finally, in future TeleLayering applications, a team of construction and supporting robots are anticipated to work together on a remote site. Planning, coordination, and interoperability protocols and advanced control systems need to be designed to implement an interconnected network of telerobots working in concert with human teleoperators while maximizing the overall productivity and avoiding collision and other issues.

V. Summary and Conclusions

In this paper, we proposed a teleoperated construction 3D printing system called TeleLayering to enable safe and efficient infrastructure construction in extreme environments on Earth and beyond. TeleLayering builds upon the existing knowledge and advances in telerobotics, C3DP, telecommunications, machine vision, VR and AR, and several other maturing technologies. A key requirement for implementation of TeleLayering technology, is to design an intuitive and reliable control and monitoring interface to provide the teleoperator with a high level of situational awareness for successful completion of remote construction tasks. Latency is also a related key consideration in design of TeleLayering systems. Low-latency TeleLayering seems to be a more viable starting point for this innovative technology, while high-latency TeleLayering seems possible after higher levels of autonomy are developed within the realm of C3DP technology.

While TeleLayering can directly benefit from several major existing technologies, extensive multidisciplinary research is needed to explore the capabilities and limitations of this construction technology in various domains.

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