Concrete 3D Printing with a Portable Robotic Arm for the construction of Bunkers and AnciLlaries (PRABAL) in Forward Areas

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Abstract: In a significant technological milestone, Project PRABAL has successfully demonstrated the construction of military bunkers using on-site 3D printing technology. This innovative project has opened new frontiers in military engineering, offering practical solutions for constructing defense structures in some of the world's most challenging environments. Using local materials, on-site printing of an Observation Post (OP) bunker in Leh under High Altitude Low Oxygen (HALO) conditions was demonstrated. The technological advancement required for the on-site fabrication of the structure includes overcoming adverse environmental conditions of extremely high UV, wind, and drying exposure. Printing in a remote access location within Leh further proves the robustness of the technology. The success of PRABAL is particularly noteworthy for operationalization under High Altitude, Low Oxygen (HALO) conditions, which limit the efficiency of mechanical systems. Producing concrete under adverse conditions of extremely high UV, wind, and drying exposure showcases the advancement in material processing and delivery systems used in 3D printing operations. Tactical planning and mobilization of resources to execute in a remote access location is the keystone to future deployment. The environment and location are typical of many military operational areas, and the project's success in these conditions marks a new era in military construction.

Introduction: Forward areas are remote access with inclement weather conditions. Creating protective structures with high protection for personnel has remained a challenge. Typically, protective structures are exposed to small-arms fire and low-level blasts. The threat perception ranges from high-velocity medium machine gun (MMG) rounds and blasts from rocket-propelled grenades (RPGs).

3D concrete printing provides a solution for rapidly deploying protective structures such as bunkers and ancillaries. 3D concrete printing also allows the development of form-optimized structures for protection. The geometric freedom provided by 3D printing allows printing shapes that provide enhanced protection for the different threat perceptions.

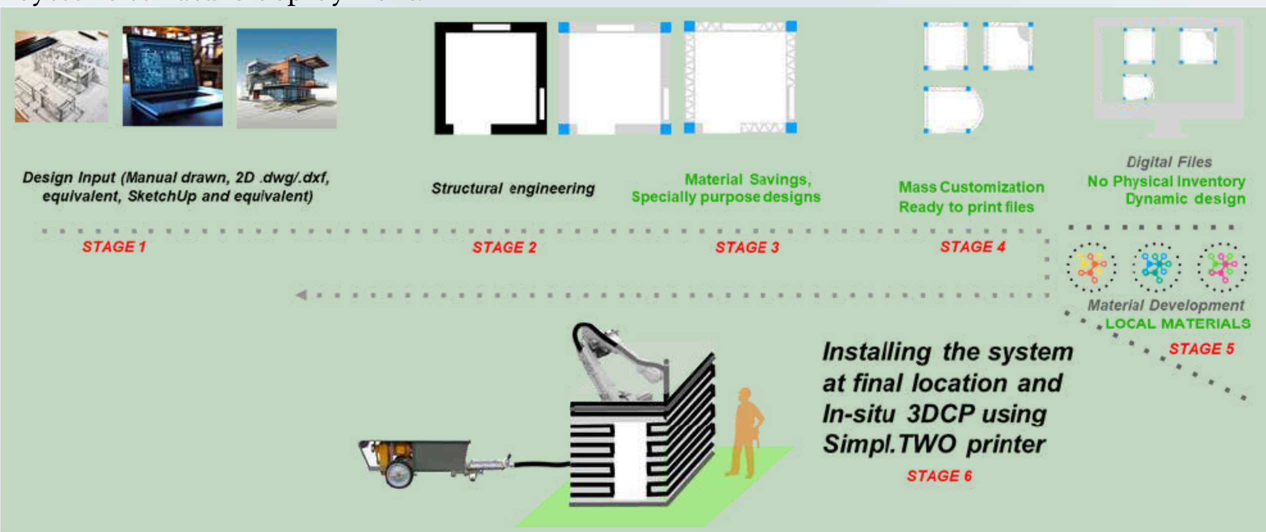


Fig 1: Development stages, including structural and dynamic design, material development, and in-situ printing.

Advantages of adopting 3D Printing by the Indian Army for deployment in forward areas include (a) Rapid Construction of defense bunkers and fortifications in remote places at a much faster pace and with limited manpower, which in turn will help in the defense preparedness of our forces; (b) Tailor-Made Structure and the freedom of design with 3D printing, when coupled with the structure's composite construction, will help design and build the structure according to the terrain and threat perception; (c) In-built camouflage and concealment based on the terrain requirement, which will blend with nature; (d) In disaster relief Operations, the rapid pace of construction will help deliver temporary shelter more quickly and efficiently; (e) The freedom in design coupled with the on-site printing will help to build the obstacles, thereby inflicting delays on the enemy advance.

3D concrete printing consists of material deposition in layers. The actual process consists of developing a layer-by-layer representation of the structure. This process, known as tessellation, creates a 3D representation of the structure for developing the 3D printed form. The material deposition contours are developed to place the material at the desired location. The entire structure is then printed by depositing the layers with material along the predetermined contours. The process of developing the digital representation of the structural design, material development, and printing the actual structure is shown schematically in Figure 1. 3D Concrete printing offers the advantage of printing complex geometric shapes form-free. The advantages of 3D printing include: (a) Structures are lightweight and efficient in performance; (b) Material is used efficiently, resulting in a reduction of wastage; (c) Structures can be fabricated in a significantly shorter time compared to conventional methods; (d) Automation and reduction in labour requirement.

Project PRABAL:

Project PRABAL, which stands for Portable Robotic Arm for constructing Bunkers and AnciLlaries, was conceived to transform how military bunkers are built. This was a collaborative project to demonstrate on-site 3D Printing of an OP Bunker with local Materials under extremely harsh environmental conditions in a remote access area. A typical view of the project site and the environmental conditions are shown in Figure 2. The project chose a typical OP bunker to demonstrate in-situ printing and the feasibility of deployment of the technology in forward areas. The site for the fabrication of the 3D-printed structure was Leh (within the Army control area). Leh allows 3D printing to be demonstrated under extreme environmental and remote operating conditions.

The project rested on four pillars: (a) Development of an all-terrain Robotic Arm for 3D Concrete Printing; (b) 3D design mixture development as per the terrain condition; (c) Optimized Structure as per the threat perception; and (d) Development of Printing strategy as per the terrain conditions site specifications.

3D Concrete Printing System

A robotic arm printing system was developed and transported to Leh. The robotic arm system, including material delivery and placement systems, was developed indigenously. A schematic and photograph of the Robotic Arm printing system is shown in Figure 3. A custom-engineered, pressure-controlled continuous pumping system has been developed to deliver 3D-printed concrete (3DCP). This system was optimized for locally sourced sand, cement, and aggregates. The system includes advanced controls for real-time monitoring and adjustments, allowing for the precise delivery of concrete mixtures tailored to the specific demands of 3D printing designs/geometry. The same pump can be used for finishing works. The system has a rubber hose of varying length and size connected to a circular nozzle.

Fig 2: The site for in-situ printing and the local conditions.

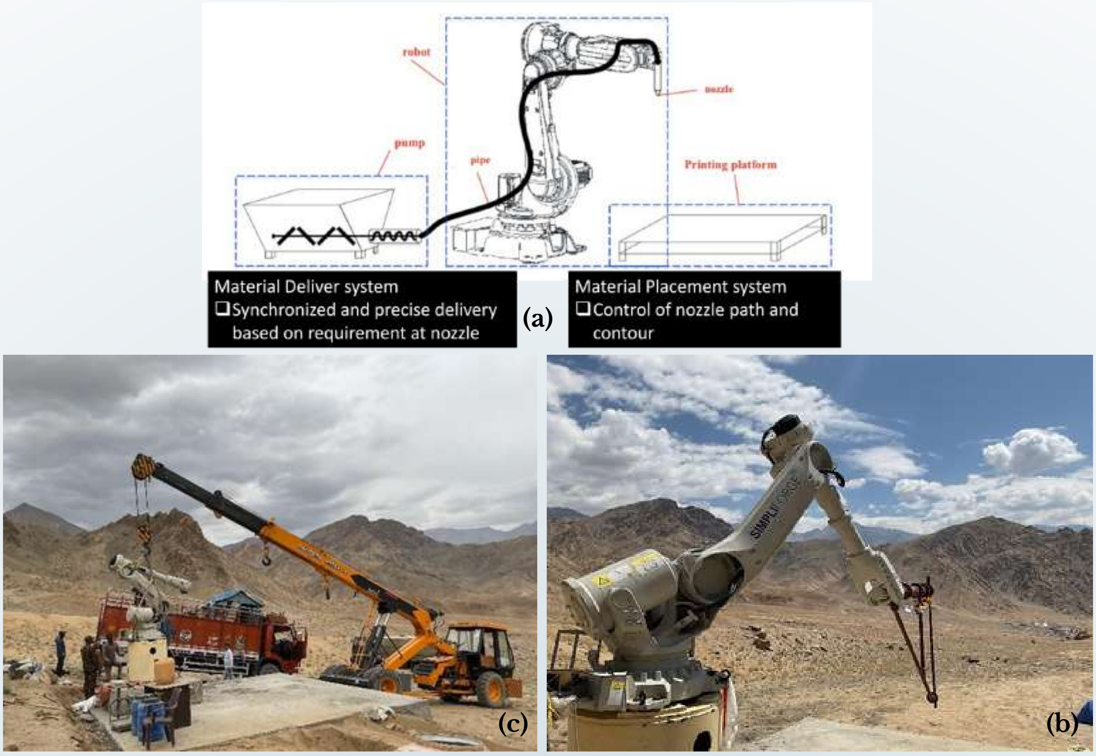


Fig 3: (a) Schematic of the robotic arm printing system; (b) The robotic-arm printing system being off-loaded on site; (c) Installation and operation of the robotic arm system in Leh.

Material ink Development

A concrete mixture is used for printing in the robotic arm printing system. An engineered concrete mixture was developed using local materials that would provide printability. This mixture ensured the structural integrity of the printed bunker, even under harsh conditions. The concrete mixture was modified to resist challenging environmental factors such as drying, quick setting, and low permeability, ensuring the material's performance in diverse conditions.

The developed concrete mixture had shape retention (held its shape after extrusion under pressure and deposition). It allowed buildability, where multiple layers could be stacked along a contour (as shown in Figure 4(a)). The printing along the predetermined contours of the OP bunker system in Leh is shown in Figures 4(b) and (c).

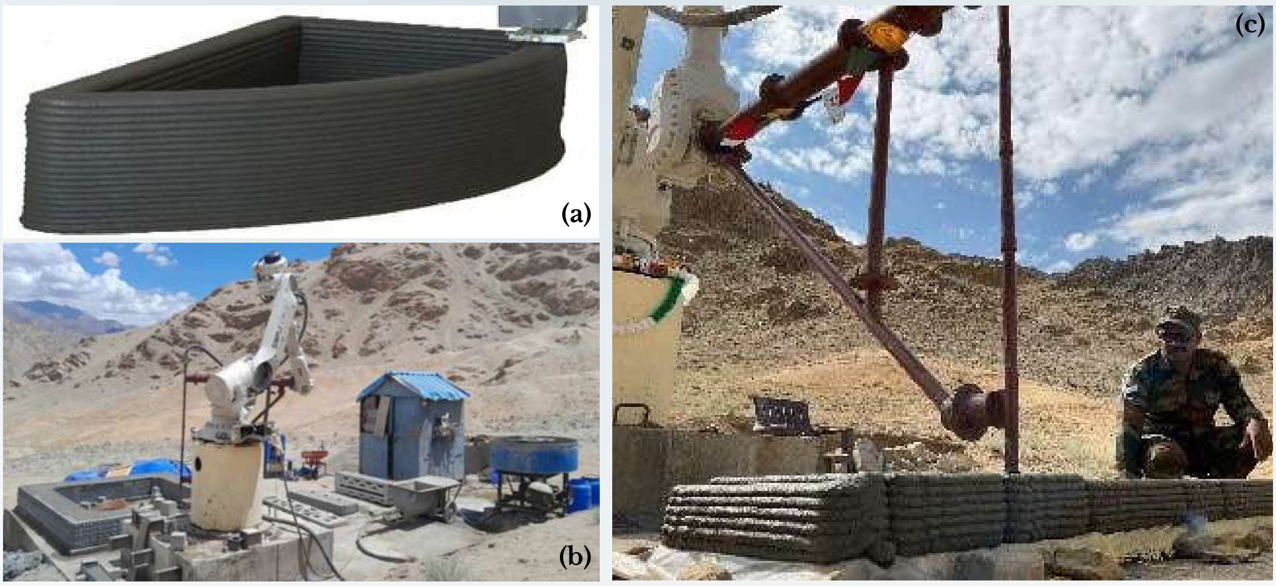
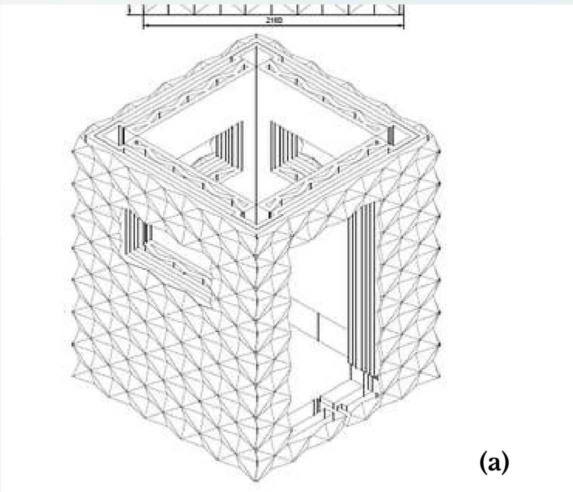


Fig 4: (a) printability testing of the concrete mixture; (b) and (c) contours of the OP bunker being printed in Leh.

A form-optimized, engineered protective structure with integrated reinforcement was developed. The form-optimized printed structure consisted of multiple layers of printed filaments with a functionalized façade. The arrangement of the filaments was developed to enhance structural resistance to blast loading.

The functionalized façade was developed for ricochet minimization. The highly functional design provided high structural efficiency at low material usage while ensuring high protection. A schematic and photograph of the form optimized functional printed form of OP Bunker are shown in Figure 5.


(a)


(b)

Figure 5: (a) schematic of the form-optimized structure; (b) the printed OP bunker in Le.

Summary

The form-optimized structure with enhanced ballistic protection was printed in ten days with fourteen hours of printing time. This project demonstrates the application of Indigenous technology for rapidly deployable structures adopting additive manufacturing principles on-site construction in forward areas, thereby increasing defense preparedness.
The project is an outcome of the collaboration of a startup company and IIT Hyderabad that has delivered on previous projects, such as the deployment of a 3D printed bridge (https://www.youtube.com/watch?v=Zjo0enwcCUU) and on-site printed medical facility with local materials for the Indian Army (https://www.linkedin.com/feed/update/urn:li:activity:7229098948399935488)

The printed bunker represents a ground-breaking milestone in military construction with advancements in material processing, design methodologies, and production procedures for fabricating structures. The pioneering work and technological advancement helped enhance the defense preparedness of the Indian Army.

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