Environment-Scale Fabrication: Replicating Outdoor Climbing Experiences

Emily Whiting[1] **Nada Ouf**[2] **Liane Makatura**[1] **Christos Mousas**[1]
Zhenyu Shu[3] **Ladislav Kavan**[4]
Dartmouth College[1] University of Pennsylvania[2]
Ningbo Institute of Technology, Zhejiang University[3] University of Utah[4]

ABSTRACT
Despite rapid advances in 3D printing, fabricating large, durable and robust artifacts is impractical with current technology. We focus on a particularly challenging environment-scale artifact: rock climbing routes. We propose a prototype fabrication method to replicate part of an outdoor climbing route and enable the same sensorimotor experience in an indoor gym. We start with 3D reconstruction of the rock wall using multi-view stereo and use reference videos of a climber in action to identify localized rock features that are necessary for ascent. We create 3D models akin to traditional indoor climbing holds, fabricated using rapid prototyping, molding and casting techniques. This results in robust holds accurately replicating the features and configuration of the original rock route. Validation was performed on two rock climbing sites in New Hampshire and Utah. We verified our results by comparing climbers moves on the indoor replicas and original outdoor routes.

ACM Classification Keywords
I.3.5 Computer Graphics: Computational Geometry and Object Modeling

Author Keywords
Fabrication; rapid prototyping; 3D reconstruction; terrain modeling; rock climbing; sports technologies.

INTRODUCTION
Fabrication at the scale of natural environments is typically out of scope for rapid prototyping technology. Although 3D printing with concrete has recently become feasible [14], the material and extrusion methods limit the ability to produce fine detail. Traditional FDM 3D printers have been used experimentally to produce house-sized structures [5], but require enormous time and financial investments. In this paper, we propose a strategic approach to fabricating large-scale environmental sites by taking advantage of how users will interact with the final structure.

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Figure 1. We capture the crux of an outdoor rock climbing route (left), fabricate the key holds and mount them in an indoor climbing wall (right). Our replica mimics the climbing experience of the original outdoor route.

We focus on outdoor rock climbing routes. In addition to representing an object which is very challenging to fabricate, rock climbing is an increasingly popular sport. Outdoor climbing areas are usually scarce and fragile and their extensive use for sport or recreational purposes represents environmental concerns. 3D printing an entire rock face would be prohibitively expensive and time consuming. We make the fabrication problem tractable by focusing only on the key aspect: how climbers interact with the site. The set of requirements for creating the same sensorimotor experience are well defined: a) configuration of the climbing holds must have the same geometry as the outdoor site; b) graspability of the contact areas (for hands and feet) must be the same; c) friction characteristics should be mimicked.

We replicate the most challenging part of an outdoor climbing route (the “crux”), starting by taking several hundred photos of the crux region and performing multi-view 3D reconstruction of the rock wall. Because fabricating the entire crux region would be prohibitively expensive, we find only the key rock features which are necessary for ascent. We do this by analyzing a video of a climber ascending the outdoor route, localizing the regions where the climber’s hands or shoe sole was supported by the rock. We isolate these parts of the rock wall geometry and turn them into physical climbing holds, similar to those used in indoor climbing walls, but replicating the 3D geometry of our outdoor wall. Fabricating accurate and durable climbing holds is a challenge and we experimented with several possibilities, ultimately choosing a rapid prototyping of physical models of the holds, followed by a molding and casting procedure. Finally, we mount the holds on the gym wall, optimizing for the best possible reconstruction accuracy subject to the constraints imposed by the indoor wall (such as given configuration of pre-installed bolt fasteners). Our current workflow assumes the route has approximately constant, vertical slope, deferring more complex rock geometries or overhanging routes to future work.

We validated our method by replicating cruxes of two rock climbing routes with differing geological features. The first route is a schist rock formation located at Rumney, New Hampshire. The second route is part of a sandstone crag near St. George in Southern Utah. Both routes are vertical face climbs suitable for our approach. We validated our results by comparing video recordings of climbers in action on the original outdoor routes and their indoor replicas. As shown in Figure 1, the moves executed by a climber on the outdoor route are similar to the moves needed to scale our replicated climbs.

We believe that replication of outdoor rock climbing problems will enhance the indoor training experience of novice climbers and experts alike, while openings new opportunities. Competitive climbers may appreciate the possibility of measuring their forces on accurate replicas of some of the world's hardest rock climbing routes. Further, setting indoor climbing routes currently relies on the skill and creativity of often professional route setters, who craft new climbing problems much like a painter creates a painting. In this light, our approach represents the analogue of photography, because we capture and "develop" climbing problems crafted by nature.

In a broader context, our contribution is a complete system for fabrication of large-scale structures which would be difficult and impractical to produce directly by 3D printing. We focus not only on the structures and their geometries, but also on how humans interact with them. While our current project focuses on replication of rock climbing experiences, we believe that the lessons learned would be applicable more generally and we provide some specific ideas in the Conclusion section.

RELATED WORK

Replicating outdoor climbing

Outdoor climbing routes serve as a natural source of inspiration for developing training tools. For example, the "Campus board," is an inclined board with thin horizontal slats that was invented by Wolfgang Güllich in 1988. Today, the Campus board can be found in many climbing gyms or even private homes. More recently, Matyas Luzan created an accurate replica of Action Directe (5.14d route in Frankenjura, Germany) in a local climbing gym [22]. Luzan sculpted hold replicas from wood, finished with varnish to replicate the texture of the rock. After 16 months and 200 training sessions, Matyas managed to climb the outdoor Action Directe on April 2015. In addition to serving as an excellent training tool, the replica spares the rock from deterioration due to frequent contact with human skin, climbing chalk, and sole rubber.

Technology for rock climbing

Indoor climbing gyms cater to climbers of all levels. Setting indoor routes of various difficulty grades is a craft which takes years to master and commercial gyms often employ a team of route setters [3]. To facilitate this process, Pfeil et al. [23] proposed an interactive system for creating routes using a simulated virtual climber. A different approach was explored by Phillips et al. [24], who generate new climbing routes from examples using machine learning and mathematics of chaos. More recent augmented reality approaches promise to revolutionize the indoor climbing experience via projectors displaying information directly on the climbing walls [12].

Another emerging technology is wrist-worn motion sensors which track the climber in action [13, 17, 18, 20]. The biomechanics of rock climbing has also been studied using instrumented indoor walls, i.e., with artificial holds equipped with built-in force sensors [2, 25]. Measuring forces on natural rock walls would require invasive installations, therefore we focus on kinematics which can be inferred from video.

3D reconstruction of terrain

Our approach has been enabled by advances in multi-view 3D reconstruction and their robust implementations [10, 11, 9]. Among recent exciting applications are Hyper-lapse videos [16], which stabilize raw video sequences captured, e.g., by a helmet-mounted camera while climbing. Aerial imagery has been successfully used to create 3D maps of famous mountain terrains such as the Eiger North Face [8] and Matterhorn (senseFly corporation). The GIS community also developed photogrammetric solutions designed specifically for vertical walls [15].

Large-scale fabrication

Scaling up fabrication technology for building-sized or environment-scale prototypes has seen recent progress. Additive fabrication of cement was made possible with the introduction of extrusion nozzles combined with contour crafting [14], but the system is targeted for construction applications where fine detail is not needed. Autodesk's Project Escher is a software solution allowing multiple extruders to collaborate in parallel for increased print speed [4]. However both these systems require a large CNC gantry. To avoid gantries, some alternative approaches employ hand-held dispensers ejecting a stick-glue composite [27] or tubes of adhesive tape [1]. In contrast to these approaches, we seek to maintain product-scale resolution using commonly available technology, while massively reducing required print volume.

ROUTE ACQUISITION

In the following sections we describe our pipeline covering the process from scanning outdoor rock walls to creating 3D polygonal models of our holds which are ready for fabrication. We aim for a technique accessible to casual users, and therefore we assume that only a conventional digital camera is used for data acquisition.

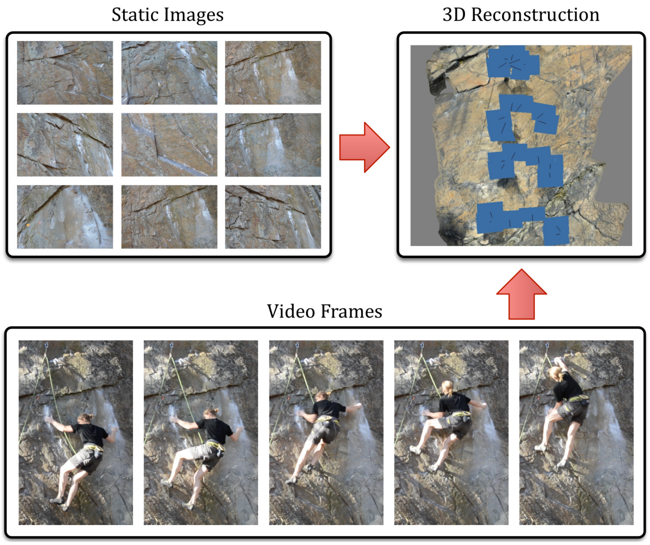

Figure 2. Close-up photos of the rock wall together with video frames are converted into 3D reconstruction using multi-view stereo.

Rock wall reconstruction

The first part of the process is to identify the "crux" region of a rock climbing route which will be the subject of our reconstruction. The size of the crux region is typically approx. 1 by 2 meters, containing the most difficult climbing moves. In our experiments, we rig the route with a top rope anchor, which facilitates close-up photography. With the assistance of a belay partner, a climber is lowered (rappelling) while taking photos of the rock wall from multiple viewpoints using a regular digital camera. This process requires only elementary rappelling skills. It is particularly important to choose viewpoints covering all of the rock features, including concavities which may be critical for climbing. For each crux, we obtain 200-500 photos with sufficient overlaps. We also capture several photos showing the rock wall along with a calibration marker which will be used to scale the resulting 3D reconstruction. Additionally, we take photos of a free hanging rope to determine the gravity direction $\mathbf{g}_{\texttt{crag}} \in \mathrm{R}^3$. Although we currently assume vertical rock walls (as opposed to overhanging or inclined), the gravity vector is important to correctly orient the fabricated route.

In addition to photos, we capture video of the climber ascending the route. The individual video frames are treated as additional images and will be used in the next step of the pipeline to determine which rock features the climber used during the ascent. We submit all images to AgiSoft PhotoScan which produces a 3D reconstruction (polygon mesh) along with extrinsic camera parameters for each image (Fig. 2). We used only one climber for each of our experiments, however, it would be possible to capture ascents of the same route by multiple climbers. In some cases, climbers of different physiques may use different holds, and this way we would be able to replicate all climbable features.

Climbing sequence analysis

The next step is to find the rock features the climber used during the ascent, which we determine by analyzing recorded

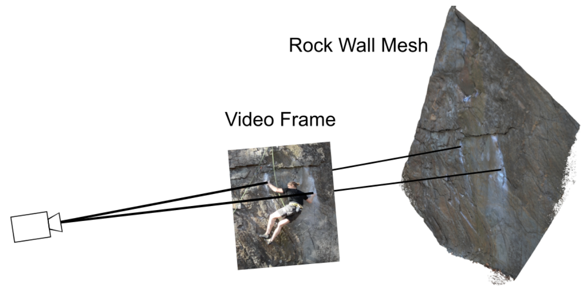

Figure 3. Multi-view stereo produces camera extrinsics which allow us to project from the image plane to the 3D scene.

video of the climber in action. We start by tracking the skeletal motion of the climber applying sum-of-gaussians motion capture algorithm [26]. We are using only a monocular RGB video stream which means the motion capture problem is ill-posed. Fortunately, we can leverage a strong, rock-climbing-specific prior: the climber's body is in close contact with the rock wall. As we already computed a 3D reconstruction of the rock wall and corresponding camera extrinsics, we can extract the missing depth information by projecting the climber's body onto the reconstructed rock wall mesh (Fig. 3). Though the climber is not two-dimensional the approximate depth information provides sufficient accuracy for our pose estimations. See Figure 4 for an example pose sequence.

Contact regions

The result of the motion-capture process is a 3D skeletal animation sequence, aligned with the rock wall reconstruction, see Figure 4. The key information is the position of the climber's hands and feet. We detect motion-less phases [21] of each of the extremities (both hands and feet). We assume that during these static phases, the extremity is in contact with the rock wall and being used to support the body weight of the climber. Though this will not always be true, e.g., a limb can be static even when hanging loosely in the air, this is rare in rock climbing moves, a loose extremity typically quickly moves towards the next available hold.

The 3D positions of the detected contact points tell us approximate locations of the key rock features the climber was using for her ascent. However, there is even more we can extract from the 3D skeletal poses: we can roughly estimate the direction of the forces, $\mathbf{f}_c \in \mathrm{R}^3$, acting between the climber's body and the rock wall. We experimented with two methods: first, we defined the approximate directions as vectors from the hip joint to each of the extremities. The second approach is to assume the force directions are aligned with the axial directions of the forearm and shin bones. We found the latter approach more accurate in our experiments since it takes into account the orientation of the limbs, rather than only considering contact points and center of mass of the climber. Fig. 5 (left) shows the contact force directions for the TATAN route. Scenarios exist where the limb directions will not align with the contact forces, but in most cases we found this to be a useful approximation.

To find the contact regions, i.e., the rock features the climber was grasping with her hands or stepping on, we calculate the dot product between our estimated contact force directions $\mathbf{f}_c$ and the surface normals $\mathbf{n}_c$ of the 3D reconstruction: $d_c = \mathbf{f}_c \cdot \mathbf{n}_c$. Values close to $d_c = 1$ mean the normals are parallel to our estimated contact forces and in compression, indicating foot holds. Similarly, d_c close to -1 indicate hand holds (contact forces acting against the normal, pulling on the rock). The most common climbing technique generally dictates that applied forces are well aligned with the surface normal to minimize opportunities for sliding failure. Therefore, we find the contact patches by executing flood fill on the triangle mesh (treating triangles as nodes, with adjacent triangles connected with edges), initialized at the contact point. The flood fill stops where d_c lies outside of our interval of interest (i.e., too low or too high d_c, depending on whether we are detecting hand or foot holds). This process terminates with a connected set of triangles which form the resulting estimate of the contact region. This contact region is inspected by the user and, if necessary, edited using a 3D painting interface. We found that this semi-automatic process provides effective guidance and considerably improves user experience compared to a fully manual pipeline. It is often challenging to locate contact regions manually, since many rock features look alike. Note that accurate measurement of contact forces is unfeasible without additional sensors, e.g., using instrumented artificial holds [2, 25].

Our current approach does not consider certain types of climbing technique such as *flagging*, where one leg hangs in the air and is used only as counter-balance, or *smearing*, where there is no prominent rock feature and the climber relies mainly on friction. In our current pipeline we labeled such moves manually and excluded them from contact region detection.

ROUTE MODELING

The resulting contact regions correspond to the 3D geometry we need to replicate in the indoor climbing experience. The next stage is to generate fabricatable 3D models which will be mounted on the gym wall.

Plane fitting

First, we determine the location and orientation of a plane representing the artificial indoor wall. This plane should be a best fit to the contact regions (to minimize the volume of material for fabrication) without intersecting any of the contact regions, which could negatively affect the climbability of the route. Let us denote the vertices of all contact regions as

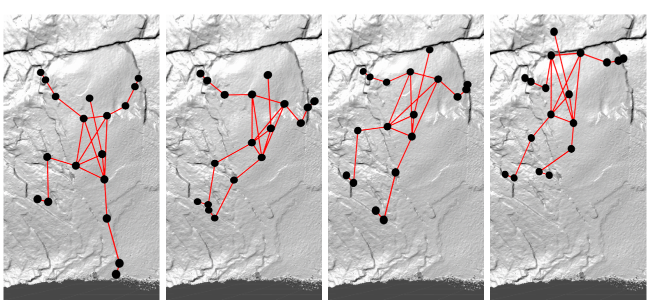

Figure 4. Rock climbing motion capture: skeletal poses estimated from a video of a climber in action.

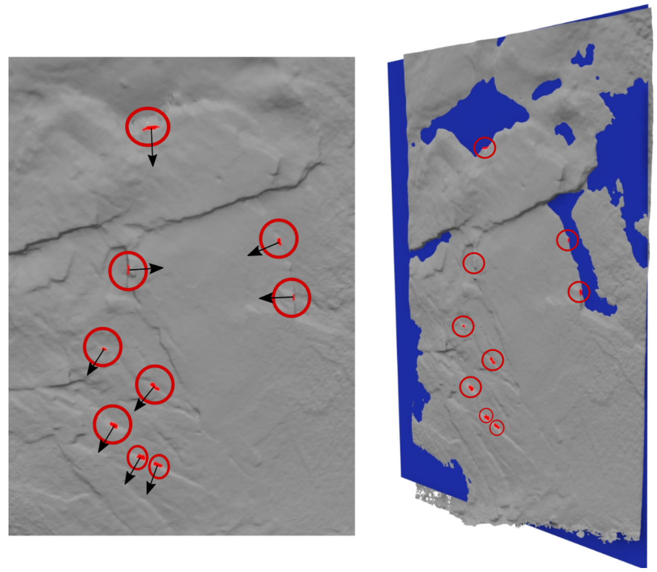

Figure 5. (Left) Contact regions and approximate contact force directions. (Right) Gym-wall plane (blue): the target for the route replica.

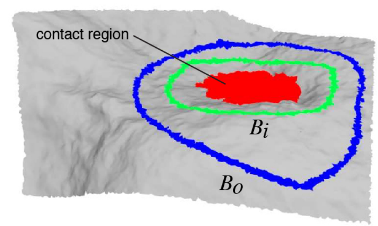

Figure 6. Estimated contact region (red) where the rock is grasped. When modeling the climbing hold, the area inside boundary B_i is unaltered. Outer boundary B_o is projected to the wall plane.

$\mathbf{v}_1, \ldots, \mathbf{v}_n \in \mathsf{R}^3$ and the gravity vector as $\mathbf{g}_{\texttt{crag}} \in \mathsf{R}^3$. If our plane is defined using a point $\mathbf{p} \in \mathsf{R}^3$ and normal vector $\mathbf{n} \in \mathsf{R}^3$, we can find the optimal plane by solving the following constrained optimization problem:

$$\begin{aligned} &\underset{\mathbf{p},\mathbf{n}}{\text{minimize}} && \sum_i (\mathbf{n}^T(\mathbf{v}_i - \mathbf{p}))^2 \\ &\text{subject to} && \|\mathbf{n}\|^2 = 1, \mathbf{n}^T \mathbf{g}_{\texttt{crag}} = 0, \mathbf{n}^T(\mathbf{v}_i - \mathbf{p}) \geq 0. \end{aligned} \tag{1}$$

This is a non-convex optimization problem with inequality constraints. The inequality constraints are essential to ensuring that none of the contact region vertices gets clipped by the resulting plane, i.e., all contact regions remain intact. We solve this problem using the `fmincon` routine in MATLAB with a variety of starting points in order to increase the likelihood of finding a global optimum. Even though other optimization methods would also be possible, we found the `fmincon` approach easy to implement and fast due to the low number of unknowns.

Hold modeling

Having defined a suitable fitting plane and contact regions, the following step is to create fabrication-suitable pieces akin to traditional indoor climbing holds. Many constraints and objectives are involved in creating fabricatable holds. We attempt to minimize material use, and at the same time the boundaries must be large enough to allow for a drilled hole that doesn't block the grasping area. Most critically, the added geometry must not alter the way the hold will be grasped, for example, introducing sharp curvature may add a graspable ledge that reduces the difficulty of the route.

We create one piece for each contact region. For each piece, we manually design an inner and outer boundary (see Fig. 6). The outer boundary, B_o, specifies the entire volume of the hold; triangles of the 3D reconstruction outside of the outer boundaries can be discarded. The inner boundary, B_i, encloses the contact region, i.e., the part of the hold which is grasped and must not be altered. The outer boundary is projected to the gym-wall plane while the inner boundary is fixed. We edit the geometry between B_i and B_o to create a smooth transition to the gym-wall plane without modifying the contact region.

To construct our prototypes we performed the editing using Sculptris. Deformation through automatic methods is an opportunity for future research, e.g., Botsch and Kobbelt [6] address the geometric aspects of this modeling problem but not the grasping, fabrication, or structural stability constraints.

HOLD FABRICATION

From the reconstruction and modeling stages we have high resolution geometry of the rock contact regions used by the climber. The modeling phase provides us with a set of discrete holds. The goal of the fabrication pipeline is to create physical prototypes from the hold geometry so they may be mounted in a climbing gym using standard hardware. In this section we detail our fabrication pipeline.

Overview

Fabrication of climbing holds presents unique challenges. Material strength must be high enough to support the body weight of a climber. The applied forces from the climber can be observed under a variety of directions and locations, as a hold could be used for both hand or foot contacts at various phases of the climb. Additionally, emulating the friction properties is essential for reproducing a realistic route. Climbers often have miniscule surface area to grasp onto, sometimes barely larger than the width of a finger. The difference between a rough or polished surface can determine whether a route is climbable or not.

Our fabrication pipeline consists of several stages:

1. We rapid prototype the 3D digital models of the holds. Our experiments used both 3D printing and foam cutting with a CNC router.

2. A flexible silicone mold is made from the initial prototype. The final solid hold is then cast from the mold.

3. Holes are drilled for mounting on a gym wall.

A summary of materials is given in Table 1. The following sections discuss fabrication methods.

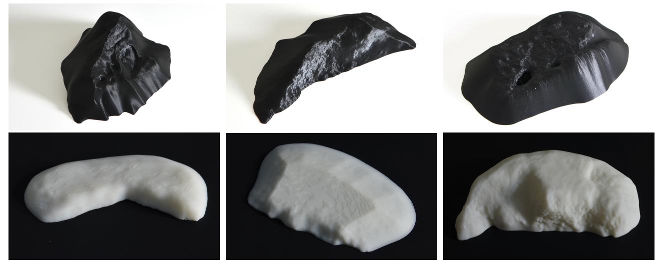

Figure 7. 3D printed holds. Geometry generated by reconstructions from natural rock formations. (Top) "Pilgrimage" route. (Bottom) "TATAN" route.

Rapid Prototyping

The first stage of the pipeline is to create a physical replica of the digital model for each climbing hold.

3D printing: To 3D print each climbing hold, we used a Stratasys Titan Fused Deposition Modeling (FDM) 3D printer with ABS plastic material. In order to conserve material, only the exterior shell is printed with sparse interior fill. See Fig. 7 for sample holds. It can be seen that the 3D prints capture natural features of the rock. To achieve texture resembling actual rock we roughen the surface by adhering sand to the surface of the print. The mold process captures these granular details.

Foam cutting: As an alternative prototyping method we created physical replicas from foam using a CNC Router. The primary motivation was improved friction: a sandy texture is inherent to the foam material, avoiding the extra step of adhering sand to surface. We used a Shopbot CNC Router with a 5/16" bit and 3-10% stepover depending on the geometry of the hold. Fig. 8 shows example holds. Compared to 3D printing, the router approach offers significant time savings – an entire piece can be cut in as little as 10 minutes (foot hold) compared to several hours for 3D printing. A limitation is in the range of geometry that can be carved. Undercuts are not feasible without a 4-axis or 5-axis machine, which tend to have smaller volume capacity and incur higher expense.

The next step is to create holds robust enough for mounting on the gym wall. Foam does not have sufficient rigidity, and 3D prints lack the surface quality to match the friction of rock. FDM printer resolution is insufficient to print a granular surface, and further, layering in FDM prints may create planes of weakness prone to fracture. Alternative materials are available for 3D printing but have disadvantages: plaster-based prints match the texture of rock but are structurally brittle. Photo-polymer prints approach the resolution of granular rock, but incur impractical high expense.

Creating the mold

Given a rapid prototyped climbing hold, the next stage is to create a mold (negative of the final product). Molds are frequently used in manufacturing commercial climbing holds. However, these practices are generally considered trade secrets and are not disclosed.

Our molds consisted of a 2-part pourable silicone rubber, Smooth-On OOMOO® 25 & 30. A bounding box is created

Figure 8. Foam holds carved with a CNC Router. Holds from "TATAN" route shown.

Figure 9. Molding & casting process. (Left) Silicone rubber poured over foam prototype to create the mold. The curing process requires 3-6 hours. (Right) Final cast climbing hold alongside its mold. Cast uses low viscosity resin which completes in under 5 minutes. The surface texture of the original foam is retained.

around the hold to limit the material volume. The silicone rubber is flexible, which allows use of a single-piece mold despite slight concavities, i.e. it was not necessary to consider problems of assembly/disassembly that would be relevant for rigid molds. The mold materials are straightforward to use: convenient 1:1 mixing ratio by volume for the liquid components and no degassing mechanism was required to remove air bubbles. The silicone material captured surface textures of the rapid prototyped hold (foam or 3D print with adhered sand), and was sufficiently resilient when used for multiple casts. The process is shown in Fig. 9.

Casting the hold

Once the mold is prepared, we create the final hold through a casting procedure. We use Smooth Cast® 300 series liquid plastic, which is a low viscosity casting resin. The fully cured plastic has high durability and toughness, rated at 4000 psi compressive strength, 3000 psi tensile strength, and 4500 psi flexural strength making it suitable for supporting applied forces from a climber. Similar to molding, casting involves mixing a 2-part pourable set of liquids in a convenient 1:1 volume ratio. Degassing is not necessary for removal of air bubbles.

Mounting the holds

As a final step, the fabricated holds must be mounted on the gym wall. We drill a bolt hole in each climbing hold so that it can be attached using standard T-nut fasteners, commonly found in climbing gyms with plywood walls. For safety precautions and to allow tightening, the bolt is sunken so that it lies below the exterior surface. See Fig. 10 for an example.

Figure 10. Fabricated holds mounted on the gym wall.

An additional challenge in the mounting process is determining hold placement on the wall. A given wall may consist of hundreds of T-nuts, and optimal positioning is a key component in replicating the original route. We generate a visual guide, as displayed in Fig. 11, which aids in constructing the final route. Our method for determining hold placement is discussed in the *Indoor Configuration* Section.

Overall, the molding & casting procedure is effective in both structural properties and cost, since molds can be re-used. The mold incurs only moderate expense ($20/hold on average), while the cast material is relatively cheap. The mold requires 3-6 hours to set, while casting completes in approx. 15 min. Compared to 3D printing each hold (upwards of 10 hours and $50-100 per print), the cost and time benefit grows the more holds produced.

INDOOR CONFIGURATION

From the previous steps, we have 3D models of suitable pieces, resembling traditional indoor climbing holds. We also know the location of the gym-wall plane. The last step is to determine *where* to drill the holes in the fabricated pieces so that they can be attached to the gym wall to resemble the 3D geometry of the original outdoor crag as closely as possible.

Process	Material
3D Printing	ABS thermoplastic
CNC Router	High density shaping foam
Mold	Smooth-On OOMOO® 25 & 30 silicone rubber
Cast	Smooth Cast® 300 series liquid plastic
Wall Mount	3/8" socket head bolt with hex drive

Table 1. Summary of fabrication materials

T-nut positions acquisition

Gym walls are equipped with T-nuts which serve as attachment points for the holds. The holds are attached using bolts and can be easily mounted and dismounted. However, the configuration of the T-nuts is fixed and cannot be changed without major construction efforts. Some gym walls have T-nuts arranged in a regular grid, but other gyms - such as ours - feature randomly perturbed positions. To find the coordinates we start by capturing a 3D reconstruction of the gym wall, following the same process as with outdoor walls, including estimation of the gravity vector and scale. We assume that our chosen gym wall is vertical and planar. In this plane we define a 2D coordinate system by picking an arbitrary origin O (typically at the base of the climb) and defining an "up vector" $\mathbf{y}$ by projecting the negative gravity vector $-\mathbf{g}_{\mathtt{gym}}$ to the plane. Because we assume the wall is vertical, $-\mathbf{g}_{\mathtt{gym}}$ should be almost parallel to the plane. The $\mathbf{x}$-vector of the basis is given by rotating $-\mathbf{g}_{\mathtt{gym}}$ around $\mathbf{n}$ by 90 degrees.

Our next task is to find the coordinates of the centers of the T-nuts with respect to the $(O, \mathbf{x}, \mathbf{y})$ coordinate system. First, we identify the T-nuts in the gym-wall photos using the circular Hough transformation (function `imfindcircles` in MATLAB), taking advantage of the fact that each T-nut has the same radius, which we can easily measure. Analogously to our motion capture pipeline, we cast a ray from the camera center though the center of each T-nut. The intersection of the ray with the gym-wall plane gives us a point which we express in terms of our coordinate system $(O, \mathbf{x}, \mathbf{y})$.

Positioning on the indoor wall

Having defined 2D coordinates of each hole in the gym-wall plane, the last step is to determine where to place the ensemble of our fabricated holds. At this stage, we only need to work with projections of the holds to the 2D plane, reducing the problem to two dimensions. Typical indoor climbing walls feature many T-nuts and therefore, there are many possibilities where to attach our holds. We aim to reproduce the 3D geometry of the original outdoor crux as closely as possible. First, we rotate all of the pieces in order to align $\mathbf{g}_{\mathtt{crag}}$ with $\mathbf{g}_{\mathtt{gym}}$, i.e., the climbing problem is oriented the same way with respect to gravity. Determining suitable translation of the ensemble is slightly more complicated. Let us denote the ideal position of the hole in each piece as $\mathbf{c}_j \in \mathsf{R}^2$, typically at the center of each piece to maximize structural stability after drilling the hole. We want to find a translation vector $\mathbf{t} \in \mathsf{R}^2$ such that each $\mathbf{c}_j + \mathbf{t}$ would get as close as possible to *some* T-nut. This leads to the following optimization problem:

$$\underset{\mathbf{t} \in \mathcal{T}}{\text{minimize}} \quad \sum_j \lambda_j \|\mathbf{c}_j + \mathbf{t} - P(\mathbf{c}_j + \mathbf{t})\|^2 \qquad (2)$$

where $\mathcal{T}$ is a set of allowed translations (user-defined rectangle in our case), $\lambda_j > 0$ are user-selected weights, and $P : \mathsf{R}^2 \to \mathsf{R}^2$ is a function which projects an input point to the closest T-nut. For a given initial guess of $\mathbf{t}$, we can minimize the problem (2) by alternating between two steps, similarly to local-global solvers [7]. In the first (local) step, we assume that $\mathbf{t}$ is fixed and we compute the closest T-nut $P(\mathbf{c}_j + \mathbf{t})$. In the second (global) step, we assume the projections $P(\mathbf{c}_j + \mathbf{t})$ are fixed and we solve a simple convex quadratic minimization problem to obtain the optimal $\mathbf{t}$. These steps are iterated until the closest T-nuts are no longer changing, at which point we found a local minimum. To increase the chances of finding a global minimizer, we sample the entire region $\mathcal{T}$ and run the above described optimization from many different initial guesses. Generous sampling is not difficult due to the low dimensions of $\mathcal{T}$ (subset of R^2). The result for our TATAN route can be seen in Figure 11. Note that our route can naturally coexist with traditional indoor climbing routes. We can evaluate the accuracy of the fit of each hold by computing the positioning error $e_j = \|\mathbf{c}_j + \mathbf{t} - P(\mathbf{c}_j + \mathbf{t})\|$ for each hold j.

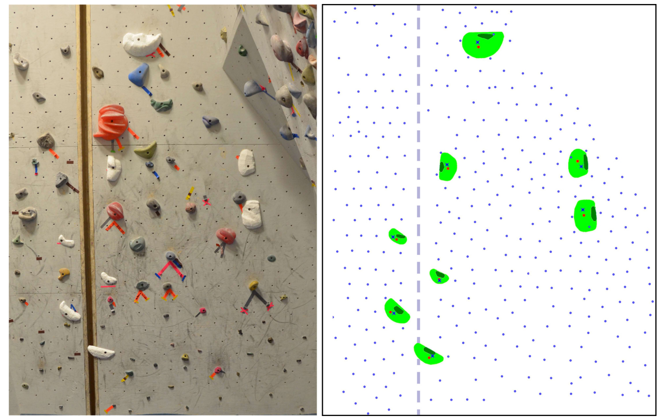

Figure 11. (Left) White holds forming our replicated route were positioned by finding optimal matching against T-nuts permanently installed in the gym wall. (Right) T-nut positions are shown as blue circles. Red circles correspond to hold centers and crosses correspond to the optimal T-nut match.

Building our prototype routes revealed that in future work it may be advantageous to augment the objective in Eq. 2. The most common failure mode of a hold attachment is rotation around the bolt due to high applied torque. We could penalize hole positions which lead to large torques under the expected loadings; note that a single hold is frequently used both as a foot *and* hand hold in different phases of the climb, so it is necessary to find an effective compromise. Another requirement is robustness. After tightening the bolt, the hold must be able to withstand large loads without fracturing. One possibility would be to study internal stresses using Finite Element Analysis. With a realistic friction model for the hold/wall interface, it would also be possible to calculate the optimal range of tightening torque, which needs to be high enough to prevent spinning, but not so high the hold would fail.

RESULTS

The poses a climber uses to ascend a route are highly constrained by the geometry and placement of the holds. As such, we chose to perform user studies as an indicative method for validating our results. We compare the corresponding poses of the same climber on 1) the original outdoor crux and 2) our indoor replica. In studies of two example routes – TATAN and Pilgrimage – we demonstrate a close visual match between the climbers poses on the original and replicated route. Both routes are vertical face climbs suitable for our approach.

Figure 12. TATAN route: Pose by pose comparison of climber A between the original outdoor route, and our indoor replication.

Theoretically, an ideal way to evaluate the climbing experience (and route difficulty) would be by measuring time-varying forces in the musculoskeletal system, e.g., muscle activations. Electromyographics studies of muscle activations during climbing have been performed before [19], however this seems feasible only in a controlled lab environment.

TATAN

The TATAN route is a schist rock formation, graded 5.12a. It is located at Rumney, New Hampshire, a popular climbing destination in the Northeast USA. We fabricated 8 holds for the crux region and replicated the route in a climbing gym. The minimum positioning error ($\min_j e_j$) was $1.1cm$ and the maximum ($\max_j e_j$) was $5.8cm$.

We obtained informal feedback from four adult male rock climbers. All four of the test climbers (A, B, C, D) had prior experience climbing the corresponding outdoor route. Our route reconstruction was based on climber A's ascent (Fig. 12) and, as shown in the accompanying video, his ascent of the replica indeed closely matches his ascent of the outdoor route. Climber B used slightly different footholds on the outdoor route and therefore his ascent of our replica was not identical (see the accompanying video and Fig. 13). This could be improved by manufacturing additional holds. We did not have reference outdoor video of climbers C and D. All four climbers unanimously agreed on the similarity between the outdoor route and our indoor replica. Feedback included that it was a close match and in particular that "the movement feels similar." As criticism, one user stated that the slope of the wall is slightly steeper making the indoor climb more challenging than the original.

Pilgrimage

The second route, "Pilgrimage," is graded 5.12a and is part of a sandstone crag near St. George in Southern Utah. We fabricated 6 holds to replicate the crux. The minimum positioning error ($\min_j e_j$) was $4.17cm$ and the maximum ($\max_j e_j$) was $12.4cm$. We had three adult male rock climbers (F, G, H) ascend our replication for the study. With our indoor climbing gym being located in New Hampshire, we did not have access to the original climber (E) in the reference videos or any climbers familiar with the Pilgrimage route. Instead, we show a comparison between static poses with two different climbers, see Fig. 14. The poses are similar but do not match as well as in the TATAN example, especially in the beginning of the crux because we omitted the reconstruction of the initial footholds, relying on features pre-installed on the indoor climbing wall. Also, the vertical positioning of the right foot in the last move (columns 3 and 4 in Fig. 14) has a different relative alignment from the outdoor climb. When finding the optimal T-nuts, the left foothold was moved down and the

Figure 13. Pose by pose comparison for climber B on the TATAN route.

Figure 14. Pilgrimage route: Pose by pose comparison between the original outdoor route (climber E), and our indoor replication (climber F).

right up, resulting in compounding of the error. In the future it may be desirable to alter the optimization objective (2) to explicitly account for *relative* errors, as opposed to the current global error.

Generally, the climbers were excited by the idea of being able to climb a replica of a route from a location more than 2000 miles away. Overall we were pleased that test climbers immediately demonstrated an interest in using the routes for training and to experience remote locations. Note the Pilgrimage route replication was accomplished in a purely digital way, i.e., no physical artifacts were transported from Utah to New Hampshire, only data (specifically, photos and videos). This "route teleportation" may prove useful in the future when attempting to replicate routes from hardly accessible areas, e.g, high mountains in foreign countries, where already reaching the base of the climb requires non-trivial logistics.

Climb analysis

We analyzed video recordings of corresponding outdoor and indoor climbs, see Table 2. The indoor time reduction for TATAN was due to the climbers' familiarity with the climbing sequence; less time was spent in each static pose, determining the next move. This was not the case with Pilgrimage, since our climbers never climbed its outdoor counterpart. On the outdoor TATAN route climber B used 5 different holds compared to climber A, but 3 out of the 5 were still present at our replicated holds (closer to the center of the crux as B was shorter than A). In the indoor TATAN replica, climber B used one extra foothold compared to climber A's ascent of the indoor TATAN, compensating for the fact that we have not replicated the bottom portions of the route. All of the crux moves were completed using the fabricated holds.

	Climb	Climber	Time	Poses	Extra Holds
TATAN	Outdoor	A	22s	6	0
	Indoor	A	15s	6	0
	Outdoor	B	27s	9	5
	Indoor	B	15s	6	1
Pilg.	Outdoor	E	6s	4	0
	Indoor	F	8s	4	0

Table 2. Results of video analysis of the climbs. Time is the total climb time measured from the start of the first static pose to the start of the last static pose.

Surface texture

In addition to testing climbing poses on the replicated routes, we gathered feedback on texture properties of the fabricated holds. We presented climbers with pairs of holds having identical geometry, but fabricated with the alternative techniques of 3D printing and foam cutting. We asked users to comment on which felt more like natural rock. The study involved 9 adult climbers, all experienced in outdoor climbing. Note that we tested the final cast holds, but refer to the alternatives as "foam" or "3D printed" to indicate the intermediate rapid prototyping method.

Seven out of nine climbers agreed the foam holds felt more like real rock. One preferred foam for a more pleasant climbing experience but did not have an opinion about realism. The last user had no stated preference. Zero users preferred the 3D printed holds. Five users specifically remarked that the foam holds felt like sandstone (matching the Pilgrimage route rock). Users appreciated that the foam holds felt more homogeneous and would maintain their friction over time. The main criticism of the 3D printed holds covered with glued sand was that they are too abrasive.

We conclude that foam is the better option for rapid prototyping, considering both realistic friction and longevity. However, since few users noted similarities to Rumney's schist rock, we are interested in continuing to analyze the factors that contribute to the natural feeling of rock varieties. In the future, it may be possible to measure the friction properties of the rock quantitatively and replicate them using fine-scale fabrication techniques.

Figure 15. Comparison of surface texture in fabricated holds. (Left) Cast from a 3D printed hold with adhered sand. (Right) Cast from a porous foam hold.

Limitations and Future Work

Our route replication workflow currently assumes climbing routes have constant inclination. Replicating the 3D architecture of rock – where planar wall approximations are insufficient – is a major challenge for future work. In the gym, our holds could be extended using e.g. wood boxes bolted to the wall (a.k.a. climbing volumes). An automatic technique to determine the box geometry and positioning would expand the range of routes we can reproduce. Another human-specific consideration is the effect of gradual muscle burnout and fatigue, critical especially with long routes. In the future, it would be possible to design training routines focusing on stamina.

Our current acquisition pipeline assumes that a climber capable of leading the route is available. In the future, we would like to explore route acquisition using e.g. drone photography to remove this restriction. Carefully planned flight paths will be essential to capturing all of the rock features including concavities. Another challenge will be the lack of reference climbing video recordings, which would be replaced e.g. by biomechanic simulations determining which climbing moves are feasible.

The problems of fabrication of large-scale artifacts are not restricted to rock climbing. Future applications might include:

- Replicating cave paintings in a museum setting. To save cost it may be preferable to reconstruct only sparse areas of interest of the cave environment. The geometric configuration of the individual paintings should be retained, as it may tell a story or reflect aspects of early human cultures.
- Reconstructing crime scenes for Forensic analysis. Physical evidence requires high detail, and relative placement may represent critical cues for understanding interrelationships between components in the scene.
- VR environments, replicating geometry of objects that invite interaction to provide tactile feedback. Virtual and Augmented Reality experiences combined with climbing are already starting to be explored in the videogame industry (e.g. *The Climb* developed by Crytek for Oculus Rift).

CONCLUSION

Our work explores a new and unusual problem in large-scale fabrication, specifically, replication of outdoor climbing walls. We focus on recreating the sensorimotor experience of the user while interacting with our replica. The main challenge of this project consisted in discovering the appropriate techniques from various disciplines (HCI, computer vision, CAD, and fabrication) and determining how to connect them to obtain a complete system capable of environment-scale fabrication.

We believe that replicating outdoor routes could impact the indoor climbing gym industry and inspire future research in environment-scale fabrication as well as related scientific and technological questions. For example, how to measure and replicate friction properties of natural materials, combining large-scale physical artifacts with Augmented or Virtual Reality, studying biomechanics of human locomotion in challenging conditions, or 3D capture of environments not accessible by regular vehicles or on foot.

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