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# CultArc3D_mini: Fully Automatic Zero-Button 3D Replicator

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**Figure 1:** *CultArc3D_mini CAD design and automatic process flow from artifact over 3D scan and 3D reconstruction to 3D print of replica.*

**Abstract**

*3D scanning and 3D printing are two rapidly evolving domains, both generating results with a huge and growing spectrum of applications. Especially in Cultural Heritage, a massive and increasing amount of objects awaits digitization for various purposes, one of them being replication. Yet, current approaches to optical 3D digitization are semi-automatic at best and require great user effort whenever high quality is desired. With our solution we provide the missing link between both domains, and present a fully automatic 3D object replicator which does not require user interaction. The system consists of our photogrammetric 3D scanner CultArc3D_mini that captures an optimal image set for 3D geometry and texture reconstruction and even optical material properties of objects in only minutes, a conveyor system for automatic object feed-in and -out, a 3D printer, and our sensor-based process flow software that handles every single process step of the complex sequence from image acquisition, sensor-based object transportation, 3D reconstruction involving different kinds of calibrations, to 3D printing of the resulting virtual replica immediately after 3D reconstruction. Typically, one-button machines require the user to start the process by interacting over a user interface. Since positioning and pickup of objects is automatically registered, the only thing left for the user to do is placing an object at the entry and retrieving it from the exit after scanning. Shortly after, the 3D replica can be picked up from the 3D printer. Technically, we created a zero-button 3D replicator that provides high throughput digitization in 3D, requiring only minutes per object, and it is publicly showcased in action at 3IT Berlin.*

**CCS Concepts**

***•Social and professional topics*** → ***Automation;*** ***•Computing methodologies*** → ***Reconstruction;*** *Self-organization;* ***•Hardware*** → ***Scanners;*** *Emerging tools and methodologies;* ***•Computer systems organization*** → *Robotic autonomy;*

## 1. Introduction and Motivation

For years 3D scanning and 3D printing have been rapidly evolving with no end of the development in view. Both domains generate results with a huge and growing spectrum of applications, and they are interconnected: Just like 2D flatbed scanners can provide data for close-to-real copies by 2D printers, so can 3D scanners serve as source for 3D printing. With a growing spectrum of technologies for multi-color 3D prints at improving quality, 3D replica get closer to the originating artifacts from day to day, and make the idea of 3D replicators come real. Especially in Cultural Heritage, a massive amount of objects awaits digitization for various purposes [SRFF17]. Digitization in 3D alone has many fields of application as well. The most obvious is conservation of cultural heritage artifacts, as a reference for conservation and restoration measures

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on damaged goods, or as basis for physical replicas. Digital documentation of significant pieces of art, endangered by environmental influences or disastrous events, is easily possible by securing the current state of conservation and making it accessible for research around the world. Collections and research results are ubiquitously available to education and the public, opening up possibilities for new research methodologies, e.g., correct reassembly of complex fossils, by applying intelligent algorithms to 3D models. For museums, 3D models open up new ways of exhibition planning and implementation, as collections spreading over multiple museums can be showcased concurrently at different geographic locations. 3D replicas, materialized in 3D printed form, are usable as exhibition and loan objects for various purposes, thereby avoiding damages and insurance costs, or legal uncertainty relating to ownership.

The need for rapid and automated digitization in 3D is also present and growing in many other fields, including the industry, where products have to be compared against their CAD models to identify discrepancies in the manufacturing process, or for showcasing products, such as apparel items, online in 3D to the customer with no CAD models available. 3D scanning and 3D printing also play an important role in rapid prototyping which gains increasing influence in the modern production process.

Yet, current approaches require a great time effort, which applies to all optical methods of 3D digitization if high quality is required, mostly for repositioning the sensor around the object. The challenge is meeting the best tradeoff between efficiency and optimum overlap between the single views to be acquired, either by a camera in the case of photogrammetry, or by structured light scanners generating a partial point cloud for each perspective. Current approaches to automation of this process are still semi-automatic at best, requiring user attention to some extent. A study conveyed by the Victoria and Albert Museum [SRT*14] shows that time for 3D digitization with texture varies between 5 and 20 hours due to manual or semi-manual acquisition (only using a rotary as automation component) and post processing, while complex materials are not even considered. Even if the rotation of the object is automated using a rotary, most systems still do not have a robotic arm or similar actuator to achieve a full coverage of the object surface by views of the sensor, so the vertical positioning of the sensor to several levels of height, necessary to achieve a complete and high quality 3D model, requires user interaction. Also, the scan control software typically requires user interaction as well for certain steps during digitization, where the level of quality desired leads to an exponential effort invested by the user.

Our solution provides the missing link between the domains of 3D digitization and 3D printing. The system consists of a 3D printer, our photogrammetric 3D scanner CultArc3D_mini, a conveyor system that transports the objects from the entry to the exit and provides exact positioning in the center of the scanner, and a software that controls the fully automatic process flow. Sensors are used to keep track of the position of objects in the system and to detect when the operator positions an object at the entry or retrieves it from the exit after scanning. The state machine-based process flow software of our solution provides seamless and safe transitions between the various complex process steps, including transportation of the object through the system, 3D acquisition of the object, 3D reconstruction from the image set captured, and initiating the 3D printing process of the resulting 3D model. From the user perspective, the process starts with placing an object at the entry, and ends with picking the original up from the exit after scanning, as well as the 3D replica from the printer after completion of the 3D print, intentionally very much like the well-established process of the 2D analog of copying 2D documents.

Our contribution is the realization of the first fully automatic 3D object replicator which is publicly showcased in action at 3IT Berlin. In detail, this contribution entails both hardware and software development:

- 3D scanner designed as a photogrammetric measurement setup capturing an image set optimized for photogrammetric reconstruction from overlapping perspectives, distributed in a homogeneous coverage over a hemisphere, under diffuse illumination to avoid shadows. The 3D scanner design consists of a distributed network of independent scanning nodes, each contributing to the image set from an individual perspective. A conveyor system was designed for object feed-in and -out and positioning in the center of the scanner, equipped with sensors for accurate positioning and detection of entry and exit. Due to the design using two independently rotating arcs, the scanner provides a platform for measurement of spatially varying optical material properties with independently controllable incoming light directions and outgoing perspectives. The small scale of the design additionally makes it perfect for higher-accuracy acquisition of optical material properties of flat samples of typical size.
- Control software achieving full automation, making the system a zero-button solution for the combined process of 3D scanning and 3D printing with zero user interaction.
- Process flow including color-calibration, intrinsic and extrinsic camera calibration, and scale calibrated to real world units.
- Low-cost setup thanks to an innovative data transfer network of distributed scanning nodes, each consisting of a low price Raspberry Pi micro computer with attached camera, and 3D printed construction parts based on our own design.
- Form factor and light weight of the setup, making it easily transportable for application at any place in the world.
- Full way to 3D replica is not mandatory, system can also serve as automatic device for fast 3D acquisition only.

The benefits are both for the domain of Cultural Heritage and the industry, as well as any other domain requiring automatic digitization in 3D at high throughput and/or 3D replication. While providing these benefits, the overall system as described here reaches technology readiness level 7 (TRL7) as it can be classified as 'system prototype demonstration in operational environment' [Wik18], and comes at a reasonable material cost of less than $EUR$ $5{,}000$ with all required components included.

## 2. Related and Previous Work

The archetype for the 3D scanner as the core component of our zero-button solution clearly is CultArc3D that is part of CultLab3D, the first fully automatic 3D scanning street for objects up to 60 *cm* size [SRT*14]. CultArc3D is the first of currently two scanning stations that captures images from a hemisphere in under 30 *seconds*, leading to a coarse 3D model of the object using photogrammetric 3D reconstruction in under 5 *minutes*. This coarse model is sufficient for the second scanning station to compute trajectories of poses for a single camera at higher resolution, mounted on a robotic arm guiding it. The trajectory defining angles for all joints of the robotic arm is computed to achieve a minimum set of additional images to be captured by the camera on the robotic arm, accounting for all perspectives that might not have been captured by the first scanning station due to cavities not resolvable from perspectives limited to a spherical distribution. In conjunction, both scanning stations combine their advantages.

However, CultArc3D can also run standalone. Its design, providing a virtual hemisphere of camera positions around the object by rotating an arc equipped with cameras, has several reasons.

First, it constitutes a trade-off between a physical sphere, equipped with many redundant static cameras, and a robotic system with a single camera. While the former is fast, but cost-intensive due to hardware redundancy, the latter is slow, as the robotic system has to reach all positions one after another, with the advantage of being much more flexible in reaching specific poses. Using an arc equipped with cameras thus is somewhere in the middle, as it requires rotation and sequential capturing for each angle, but also provides parallel capturing of all cameras on the arc. A hemisphere as such is the geometric shape that provides the best coverage for photogrammetric 3D reconstruction, as the cameras are all looking towards the center and are homogeneously distributed, with sufficient overlap between neighboring views to account for SIFT (Scale-invariant Feature Transform) features that are vital for this type of image-based reconstruction, which relies on the Multi-View Stereo (MVS) algorithm [GKA*10].

The second reason for an arc architecture is the easy integration of automation technology for object transportation inside of the scanner and out, as in the upright position of the arcs, the object can freely travel inside of the virtual hemisphere, which would be difficult in the presence of an obstructing physical hemisphere.

And the final reason for an arc structure is the acquisition of optical material behavior: When a second arc is used that shares the same axis of rotation and has an analogous distribution of ring light sources, the two virtual hemispheres of cameras and light sources lead to a combinatorial set of incident light directions and viewing directions that, according to current state of the art in optical material properties acquisition [SRFF17, SRF*17], represent the behavior of surface materials best. One of the approaches to material acquisition so far that in turn inspired development of CultArc3D is [SWRK11], a setup called the DOME with a hemisphere equipped with fixed cameras and light sources, which was improved by using a quarter arc rotating around a vertical axis and LED lights replacing the consumer camera flashlights [SK12]. Another inspiring approach was the ORCAM built at DFKI [NKRS15] which comprises a full sphere, thus allowing for capturing the bottom of artifacts placed on a transparent glass carrier. However, these systems lack the possibility of automated object transport, which is made possible by the arc construction of CultArc3D with an integrated conveyor system. The 3D scanning system we propose as core component of the zero-button 3D replicator follows the design of CultArc3D, but is realized as a smaller version at a scale of 1 : 2.2 with improvements as outlined in Section 1 that make it more suitable for the intended use.

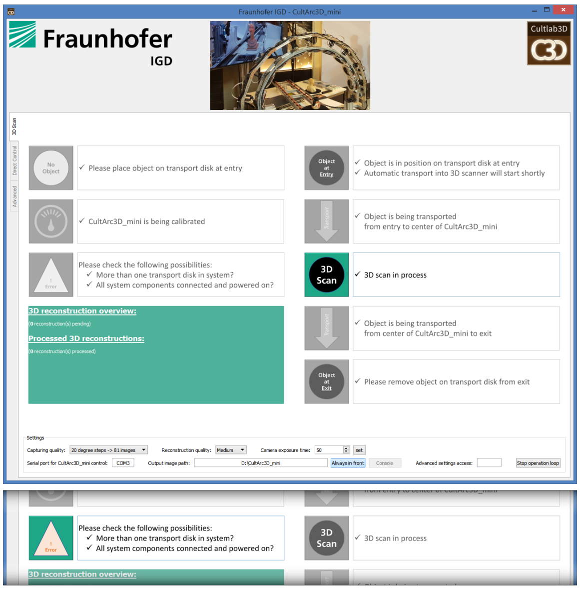
3D printing has undergone rapid development, especially on the software side. Not only can colors of prints be matched very closely to colors of real objects (see Fig. 4 (right) in Section 4), but even material effects such as translucency and gloss can be emulated, using multi-channel printers and a special printer driver, such as Cuttlefish [BAU15]. The more the 3D print is to match reality, the higher are the requirements for quality of illumination and capturing. Our ongoing research in the field of optical material behavior acquisition and its tight coupling with the use of the acquired information for 3D printing will open up ways of realism for physical replica far beyond current approaches of multi-color acquisition and printing.

## 3. Approach

The primary components of the zero-button 3D replicator are a photogrammetric 3D scanner and a 3D printer, combined with an integrated object transportation system, to reach full automation and high throughput while accurately positioning objects in the center of the scanner as well as feeding objects in and out, and keeping track of their current position in the system. On the software side, a photogrammetric 3D reconstruction solution was integrated into the process flow which requires a software interface such as an Application Programming Interface (API) or a scripting interface. The most important component is the process flow control software that connects all above constituents and establishes a safe, error-tolerant process flow.

The idea of a zero-button solution is that it does not require user interaction with the control software, but at the same time offers seamless and fault-tolerant human-machine interaction for the only tasks left for the user to do, which are placing an object at an entry point and removing it from an exit point of the system after digitization, and retrieving the resulting physical 3D replica from the 3D printer. We solved this challenge in a way that at the same time provides maximum safety regarding moving machine parts (the two rotating arcs), in that we covered the 3D scanner with a half-barrel plexiglass housing that still allows full visibility on the entire process of digitization. The conveyor system for object transportation exits the hull on both face sides through small gates, such that the respective conveyor ends provide an easily accessible point for object entry and exit. Taking into account that the system should be appropriate for digitization of sensitive artifacts from the Cultural Heritage domain, round carrier disks are used as an interface between objects and the transportation system as the only point of contact during the entire process while the object travels through the system from entry to exit.

Once the user positions the object at the entry point, the conveyor system detects the presence of the object. To avoid user interaction, a timeout is applied after which, if no movement was registered, the object is fed into the 3D scanner and positioned accurately in its center. Then the 3D scanning process is started, involving a sequence of angles for both camera and light arc around their common axis. The union of all camera positions reached by driving the arcs to the angles within the sequence is a virtual hemisphere around the object, the center of which coincides with the center of the object carrier disks. See Fig. 3 for a visualization of the perspectives from which images are captured. For each angle, all light sources are activated, and all cameras trigger simultaneously. The arcs subsequently move into the next position until capturing is complete for all angles, at which time an image set has been accumulated from all perspectives on the virtual hemisphere around



✓ Please place object on transport disk at entry

✓ CultArc3D_mini is being calibrated

Please check the following possibilities:
✓ More than one transport disk in system?
✓ All system components connected and powered on?

**3D reconstruction overview:**
(0 reconstruction(s) pending)

**Processed 3D reconstructions:**
(0 reconstruction(s) processed)

✓ Object is in position on transport disk at entry
✓ Automatic transport into 3D scanner will start shortly

✓ Object is being transported
from entry to center of CultArc3D_mini

✓ 3D scan in process

✓ Object is being transported
from center of CultArc3D_mini to exit

✓ Please remove object on transport disk from exit

Settings
Capturing quality: 20 degree steps -> 81 images
Reconstruction quality: Medium
Camera exposure time: 50
Serial port for CultArc3D_mini control: COM3
Output image path: D:\CultArc3D_mini
Advanced settings access:

Please check the following possibilities:
✓ More than one transport disk in system?
✓ All system components connected and powered on?

✓ 3D scan in process

**3D reconstruction overview:**

**Figure 2:** *Process flow control software with visual feedback of the current system state for regular state during 3D scanning (top) and error state with suggestions of solution (bottom).*

the object. At this moment, two steps are initiated in parallel: The object is fed out of the system and halts at the exit point, while at the same time, the image set is transmitted to the 3D reconstruction module, and the reconstruction process is initiated. As soon as the previous object is picked up from the exit point, the system is ready to feed in the next object. The control software monitors the reconstruction process and sends the resulting 3D model to the 3D printer software, triggering the process of 3D printing. In case of reconstruction failure, e.g. due to materials such as transparent or mirroring surfaces failing to reconstruct, 3D printing is skipped and the user is informed. Due to the decoupled processes of capturing and reconstruction, objects can be fed through the system at constant rate, while the respective new reconstruction jobs are queued until processing capacity is available.

The result of 3D digitization is a colored 3D model consisting of a surface mesh (including vertices and normals) with one or more images containing textures that are mapped to the surface. If a color printer is connected, the resulting 3D replica can be very close to reality (see Fig. 4 (right) in Section 4). To provide the data required for physically realistic materials, the 3D scanning system needs to acquire more than geometry and texture: The behavior of the object surface in reaction to incoming light from specific angles. By capturing the combinatorial set of incoming light directions and outgoing perspectives homogeneously distributed over a hemisphere around the object, optical material behavior can be acquired. Capturing surface material behavior, even including volume light transfer, is already supported by CultArc3D_mini. The evaluation and compression of the considerable amounts of data, resulting from the large number of images captured, into an interchangeable file format, are still subject to ongoing research.

In the zero-button solution, all process steps of the system are performed in an unattended way, as opposed to a system where the single process steps are triggered each by a human after checking that the preconditions for safe continuation are satisfied. Consequentially, the process flow control software carries great responsibility when integrating all hardware subsystems and software modules while guaranteeing synchronization and in-order execution of physical actuation and software processes. We ensure safety for objects and the operator by designing the control software as finite state machine that maps all allowed situations, including sensor inputs of the conveyor system and the status of subsystems, to unique states, and ensures safe state transitions from the current state into the next, excluding the possibility of inconsistent states. To keep the complexity of the proof of concept system reasonable it does not feature a possibility to digitize the underside of objects. For the same reason, CultArc3D is operated in standalone mode without the second scanning station of CultLab3D, leading to lower quality results especially in the presence of cavities and occlusions, but providing a perfect source for fast 3D digitization for the purpose of 3D replication. It is possible to send an object twice through the system, once in inverted orientation, to obtain a complete reconstruction including the underside. Fusing the two partial scans is possible due to intrinsic and extrinsic camera calibration, but currently not included in the automatic process flow, and involves one manual step. In the automatic version with one pass, the resulting hole(s) resulting from missing data of the underside are automatically closed during the process of 3D print preparation of the 3D model, and texturing information from neighboring camera perspectives are used for interpolation, resulting in a flat underside of homogeneous color. In a subsequent setup, the second scanning station can be integrated as well at smaller scale to target objects of higher complexity, or CultLab3D can be upgraded to a 3D replicator at larger scale by adding a 3D printer and integrating the process flow control modules contributed by this work that provide the bridge between 3D digitization and 3D printing in a fully automated way.

As method of digitization we chose pure photogrammetry. First, because the same exact setup allows for both acquisition of geometry and texture as well as optical material behavior, just by changing the acquisition process, involving the mode of actuation of arcs and light sources. Second, because adding additional methods such as laser line or structured light add complexity, both in hardware and software. For a higher quality setup these additions are certainly to be considered, as this is already done for CultArc3D. The potential negative aspect that photogrammetry requires structured surfaces to work is compensated by the fact that laser-based approaches, e.g., tend to face difficulties with shiny and reflective materials, whereas photogrammetry is more robust, given sufficiently diffuse illumination. Third, from the Cultural Heritage perspective, photogrammetry provides the most passive influence on artifacts, as it only requires diffuse soft lighting, as opposed to laser or structured light which expose the artifact with higher radiation intensity.

## 4. Implementation

The implementation of the Zero-Button 3D Replicator involves a number of complex mechatronics hardware modules as well as software modules to control the process flow. In order for the system to be autonomously operating, all modules have to be integrated and interlinked, while the challenge on the software side is to synchronize all modules to guarantee in-order execution of hardware actuations and software processes, while accounting for robustness throughout the entire process chain.

### 4.1. Photogrammetric 3D Scanner

The scanning setup consists of two rotating arcs that share the same axis of rotation and have slightly different radii so they can be nested. Both arcs can cover a hemisphere around the object in the center by rotating from the vertical position to $\pm 90^\circ$. The hemisphere midpoint coincides with the center of the object carrier disks. While one semi-circular arc ('camera arc') is equipped with cameras in equiangular spacing, implemented as network of capturing nodes (Section 4.1.1), the other arc ('light arc') is equipped with the same number of diffuse light sources (Section 4.1.2). The distribution of cameras and light sources on the respective arcs is such that the optical axis of each camera goes through the center of one corresponding ring light on the other arc and ends on the midpoint of the object carrier disk when positioned in the center of the scanner. Fig. 3 visualizes the angular distribution of cameras and ring lights. The position of an object carrier disk is indicated as black circle. A bounding cylinder defined by the red and black circles defines the maximum volume of objects to be digitized. The limitation is required first because of the limited conveyor system width and the entry and exit gates of the system housing. The reason why this volume, however, is defined first, even before designing arc radii and conveyor system width, is the challenge of finding a suitable lens for the image sensor that has a depth of field range wide enough to keep the entire object in focus without modifying the lens focus setting. The angular spacing on the hemisphere is defined by the angular spacing of the camera distribution on the camera arc. The angle increments by which the camera arc is rotated during acquisition is chosen such that the angular spacing is identical for both dimensions (along the camera arc, and around the rotation axis). The light source spacing on the light arc is defined analogously. If there are $N$ cameras on the camera arc, a total number of $N^2$ camera perspectives follows. In our setup, there are 9 cameras, leading to an image set of 81 images that is basis for 3D photogrammetric reconstruction. The acquisition process for geometry and texture is performed by rotating camera and light arcs simultaneously to angles between $10^\circ$ and $170^\circ$ in steps of $20^\circ$, $10^\circ$ or $5^\circ$ angular resolution, according to the setting in the control software. While the setting of $20^\circ$ as in Fig. 3 leads to a balanced longitudinal and latitudinal distribution of perspectives, finer settings decouple both dimensions and lead to a finer sampling around the rotation axis, which improves the resolution of object cavities and occlusions in the later 3D reconstruction process. The 3D Replicator measures about 2.3 $m$ in length, 1.51 $m$ in width and 0.96 $m$ in height (housing included). Objects can measure up to 24 $cm$ in diameter and 45 $cm$ in height. The entire system with housing weights about 60 $kg$.

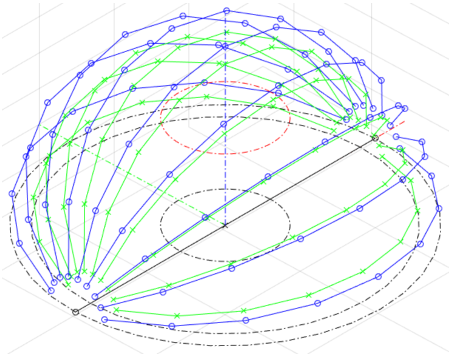


**Figure 3:** *Visualization of the angular distribution of cameras (blue) and ring lights (green) over time for one full geometry scan, achieved by rotating the camera and light arcs (indicated as connected line segments) to* 9 *angles at* $10^\circ..170^\circ$ *in* $20^\circ$ *steps.*

#### 4.1.1. Network of Capturing Nodes

In addition to a smaller scale of the construction, CultArc3D_mini differs in yet another point from its larger archetype. We have reduced one of the largest cost contributions in replacing industry cameras by a network of independent capturing nodes. Each node consists of a Raspberry Pi micro computer with an 8 Megapixel Sony IMX219PQ sensor and lens attached to it. All nodes are connected over Ethernet to the host computer. Every node runs a Linux based operating system, and our client software on top which is responsible for grabbing images from the camera sensor. On start-up, the host computer enumerates all connected camera modules, and can then individually address each using their assigned IP addresses. Subsequently, the host can adjust camera settings, such as exposure time and ISO sensitivity, and can trigger the image grabbing process. Upon receiving the capture command, each capturing node retrieves an image from the sensor, and transmits it to the host computer over Ethernet. This process runs in parallel for all nodes, so the process flow control software on the host computer synchronizes all capturing threads by waiting for a complete image set from all cameras, and then commences acquisition for the next arc angle. Due to this architecture, the camera arc can be extended to an arbitrary number of capturing nodes. Our setup is equipped with 9 scanning nodes and 9 ring lights.

#### 4.1.2. Diffuse Illumination

The choice of illuminants needs to satisfy two, at first seemingly complementary, goals. During geometry acquisition, illumination needs to be as diffuse as possible to avoid shadows on the object. In contrast to this light situation, material behavior acquisition requires specific incident light angles, ideally point light sources. In a subset of combinations, the incident light direction and the outgoing observer direction are the same, which means that in the theoretically optimal case, light source and camera are one. We achieve this complementary requirement by our design of diffuse ring lights, consisting of high power LEDs aligned in a circle that are covered by a diffusor disk. When during geometry acquisition both arcs rotate synchronously, each camera is surrounded by one corresponding ring light, which allows the camera frustum to pass through without obstruction of view. While all cameras are capturing in parallel for a specific angle of the arcs, all light sources are activated. Due to the diffusor disks in front of the LED rings, the union of diffuse light sources over the entire arc nearly act like a diffuse soft box as used in professional photography. On the other

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hand, the ring light sources are sufficiently small in diameter such that in relation to the distance from the object they approximate point light sources. For the special case of light direction and viewing direction being identical, the ring light, evenly surrounding the camera, is a good approximation of the theoretical requirement. The ring lights are individually controlled by a micro controller attached to the host computer and can also be dimmed individually.

#### 4.1.3. Optical Material Behavior Acquisition

The various material models to classify real materials currently used differ especially in their dimensionality. The 4D Bi-directional Reflectance Distribution Function (BRDF) captures the behavior of a single surface point as a representative for an entire object surface for different light and viewing directions. If local structures and patterns of a surface are to be captured, a Bi-directional Texturing Function (BTF) is suitable that can be interpreted as a 2D matrix of independent BRDFs [WLL*09]. The higher the dimensionality, the higher the degree of realism due to the amount of material-specific effects covered. At the same time, memory and computing requirements increase due to the large number of combinations originating from the set of samples for light and viewing direction combined with the size of the 2D matrix corresponding to the spatially varying discretization of the material surface measured, e.g. using a matrix camera sensor. For a BTF to be acquired, images have to be captured for the combinatorial set of each possible pair of one incident lighting direction and one outgoing perspective, taken from the hemisphere of camera positions and light source positions, respectively. This leads to set of $(N^2)^2 = N^4$ images. A tradeoff can be achieved by the Approximate Bi-directional Texturing Function (ABTF) [RSF18] that observes the surface of a flat sample surface from a single camera under a hemisphere of lighting directions. All of the above material models can be acquired using CultArc3D_mini, thus the measuring setup chosen for the zero-button replicator is ideal for combination with 3D printing technology that is rapidly evolving and will soon reach a state where material models such as BRDFs and BTFs can be realized in the 3D print. Up to date it is already possible to create volume transparency and reflectance [BAU15].

The reason why CultArc3D_mini consists of two independent arcs for cameras and light sources, sharing a common axis of rotation, is exactly to enable it to measure optical material properties. The combinatorial set of images for incoming illumination (ring lights) and outgoing perspective (camera) is captured in that both arcs move independently. The camera arc is rotated into N different angular positions, for each of which the light arc is rotated accordingly into N different positions, during which each of the N ring light sources are activated in turn, as opposed to 3D geometry acquisition, where all light sources are activated simultaneously to create diffuse lighting. The CultArc3D_mini setup uses $N = 9$ cameras and light sources, leading to an image set of $= N^4 = 6,561$ images. The arc design introduces some degree of parallel processing, as for each light position, all cameras can trigger simultaneously, leading to $N^2$ mechanical actuations during the entire process, as for each positioning of the two arcs, all 9 ring lights are activated in turn while the system stays in position, and per light position, the entire group of 9 cameras is triggered. The entire capturing process requires about 12 $minutes$.

### 4.2. Conveyor System

The purpose of the conveyor system is to allow for high throughput through the 3D scanner and at the same time to establish safety for the operator by abstracting the system to a housing with defined points of entry end exit. Round aluminum carrier disks of diameter 24 *cm* are used as an interface between objects and the transportation system (see Fig. 1). The safety of Cultural Heritage artifacts is increased as well by these two aspects, since the only point of contact between system or operator and the artifact is during positioning at the entry and removing from the exit of the system. In the meantime, the object rests safely on the carrier disk without any contact and at a safe distance to moving system parts. Positioning and pickup of the artifacts is done at freely accessible points without any obstruction potentially endangering the transport of the artifact, and can be handled by curators or personnel versed in handling cultural heritage artifacts. The conveyor disks are coated with a structured background to support photogrammetric registration of camera views, for which SIFT features are used that depend on structure. Aluminum was chosen as material because the system uses induction sensors to determine the position of the disks. The current implementation of the system is for proof of concept of one of the first fully automatic 3D replication systems and consists of low-cost components. This is why the conveyor transport is not guaranteed to be entirely smooth, while the safety of even delicate objects is not impacted, as several tests have shown. A follow-up version with higher quality cameras and light and improved automation parts is intended (see Section 6) which will optimize this aspect and will be suitable also for high value artifacts. For high throughput it is also possible to connect the conveyor entry to an automatic object storage system and the exit with an output buffer to ensure continuous operation.

### 4.3. 3D Printer

As 3D printer integrated into the 3D replicator we chose the unicolor Dremel 3D Idea Builder 3D40 to match the low budget 3D scanning solution. It is connected via USB to the control computer. The process flow control software monitors the 3D reconstruction process and sends, after successful completion, the 3D model in .obj file format to the printer (Fig. 4, middle). The 3D printing process can be automated due to the fact that virtually no post-processing is required thanks to the hemispherical coverage of camera perspectives and automated cropping against the carrier disk plane (see Section 4.5 for details). A high quality 3D replication in real colors is possible too thanks to current developments in the field of 3D multi-material printing. Fig. 4 (right) shows an example of a full-color print.

### 4.4. Process Flow Control Software

While the hardware designed for this system is vital for full automation, the software is crucial for coordination and synchronization of the process flow and data handling, including camera frame grabbing and image based 3D reconstruction. The process flow control software coordinates all hardware subsystems and software modules and guarantees synchronization and in-order execution of physical actuation and software processes. Another major task of

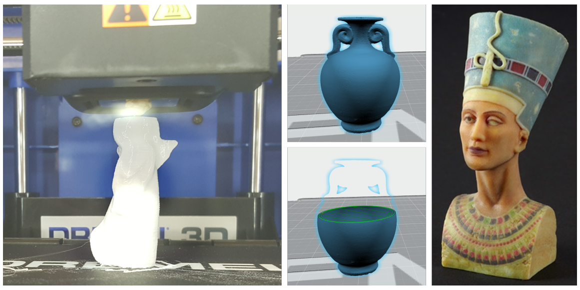

**Figure 4:** *3D print in process (left), per-layer preview of 3D print for 'Greek Vase' (middle), and full color 3D print of 3D model acquired by CultArc3D on a Stratasys J750 (right).*

the software is data handling, first by providing the reconstruction process with the captured image set, and after detection of reconstruction completion, initiating the 3D printing process by submitting the resulting 3D model to the printer. Also, the software module is responsible for initializing all subsystems, such as camera nodes, light sources, mechanical actuators and the conveyor system after first power-on, and continuously verifying that all subsystems are operational. The process flow control is realized as a finite state machine that contains valid states for each expected combination of conveyor system sensor states and current status of the 3D scanner. Fig. 5 shows a simplified illustration of the finite state machine and its transitions. Every state allows a certain combination of the three capacitive sensors located at the entry, center and exit of the conveyor system. The three inductive sensors at the system entry, exit and center react to the metal object carrier disks and trigger once a disk is above their position. The control software uses this information to identify the presence and position of objects autonomously, effectively making user interaction with the control software unnecessary, as long as the system is operating normally, thus the classification as zero-button machine. Safe state transitions from the current state to the next are ensured, as inconsistent states cause the control flow to go into the safe error state 'System Error' in which all mechanical systems are stopped. Any communication problem with the actuators or significant positional deviation as well cause a state transition from any current state to the error state (indicated by an asterisk (*) in Fig. 5). From the error state, recovery is either possible by the system itself by reinitializing the hardware interfaces, or with the assistance of the operator. Suggested steps of recovery are indicated on the visual output of the process flow control software (see Fig. 2, bottom). The visual output reflects the current system state at any given moment, every transition of the state machine can be followed in the graphical state scheme.

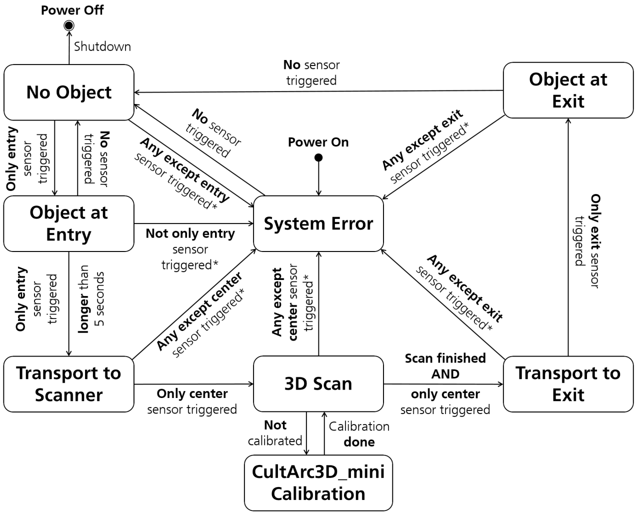

**Figure 5:** *Simplified visualization of finite state machine as core of the process flow control software to ensure safety during operation of actuated parts.*

Immediately after powering on the system, the state 'System Error' is entered by default (indicated as entry point 'Power On' in the state diagram above the error state). As soon as all preconditions for safe operation are satisfied, which includes that all hardware actuator interfaces are operational, and no sensor is triggered, the system enters the state 'No Object'. In the user interface, the user is asked to position an object on a carrier disk at the entry. If an object is present at the entry of the system, the respective state is entered, and transition to the subsequent state 'Transport to Scanner' is granted after the object stays at the entry position for at least 5 seconds. The actual 3D scan represented by the respective state is started once the object reaches the center of the CultArc3D_mini. If the state is entered for the first time after powering on, the system enters 'Calibration', which in this context refers to mechanical calibration, during which the arc actuators perform a reference search to bring both arcs in exact vertical position. The state machine represents a repetitive process, from entering of an object, transportation to the 3D scanner, the 3D scanning process, transportation to the exit, and removal by the operator. The state diagram alternatively also provides an exit point 'Power Off' which can be reached from the state 'No Object' by shutting down the system once there is no object left in the conveyor system.

### 4.5. Photogrammetric 3D Reconstruction

The 3D reconstruction module is loosely integrated into the overall system. Basically every photogrammetric system can be used as long as it provides an API (Application Programming Interface) or a scripting interface for access by the control software. We have achieved good results with AgiSoft PhotoScan (`http://www.agisoft.com`), but also freely available MVS (Multi-View Stereo) solutions such as MVE (Multi-View Environment) [FLG14] can be used as reconstruction software. There are two reasons why results generated on the basis of image sets captured from CultArc3D_mini do not need post-processing. First, the hemispherical coverage of camera perspectives guarantees that each point on the object surface to be reconstructed is visible in several neighboring cameras. Using a threshold that controls the minimum number of camera views covering the same surface point automatically filters out fragments that are part of the background, e.g., or artifacts caused by noise in the image data. The second reason, especially why the carrier disk itself is not reconstructed together with the object, is that we apply sev-

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eral types of calibration. One calibration method determines the exact scaling of the object. While scale typically is one degree of freedom for MVS, it is fixed in our solution such that a direct reference between the virtual model and the original object size is established, allowing for virtual measurement of distances and sizes in real world units. This is achieved by calibrating the camera extrinsics using ring board targets with known measured distances. This information is directly supplied to the reconstruction process and results in an accuracy that is limited by the accuracy of the 3D reconstruction, which in turn is bounded by the ratio between camera resolution and the distance between camera and object surface. In the same way, the 3D reconstruction is aligned with the carrier disk plane, such that its coordinate frame is in alignment with the coordinate frame defined by the orientation of the calibration target which is placed in the center of the carrier disk. Consequentially, the 3D model faces forward when displayed in 3D, according to how the original was positioned on the disk. This makes one automatic post-processing step after reconstruction possible: Cropping the model against the plane defined by the carrier surface, thereby effectively removing unwanted parts of the disk surface that have been reconstructed together with the object. Also, for photogrammetric 3D reconstruction it is essential to perform intrinsic and extrinsic camera calibration for each combination of image sensor and lens. And finally, we perform color calibration by first adjusting the exposure time of each camera individually to the optimal dynamic range, and then creating an ICC profile using a reference, e.g., an X-Rite ColorChecker, under the target illumination condition as it will be during the digitization process. A prerequisite for color calibration is capturing of RAW images for which we apply our own demosaicing. The ICC profiles are later reapplied in the final stage of texture mapping as part of the photogrammetric 3D reconstruction.

**Figure 6:** *Comparison of original objects with their 3D printed replica.* ***Top****: 'Bust' printed at scale 12% on Dremel 3D40 (enlarged view).* ***Bottom****: 'Greek Vase' printed at scales 18% (black) and 95% (white) on Ultimaker 2+.*

## 5. Results

### 5.1. 3D Reconstruction and 3D Print

In Fig. 6, example objects digitized with the system are shown, next to their replications (unicolor). If the low-cost 3D printer is replaced by a multi-color system, very realistic replications are possible, as Fig. 4 (right) in Section 4 demonstrates. Integration of various 3D printers is possible based on their compatibility with Cuttlefish [BAU15], a 3D printing driver that can control most multichannel 3D printers to produce compelling color and material effects. Fig. 7 (top) shows that with a relatively sparse image coverage of 81 perspectives over a hemisphere, still a fair amount of details can be reconstructed. Especially in the view from behind the object, a large cavity going deep into the object was resolved. The short acquisition time of under 2 *minutes*, however, shows visible drawbacks in the surface resolution of the 3D reconstruction. If, in contrast, the arc is moved at angular steps of 5° instead of 20°, the image set is extended to a size of 297 images. This leads to two improvements: The coverage of the object surface with image data is much better as there is more overlap and redundancy between neighboring images. Higher coverage, especially due to the finer angular distribution of perspectives, helps greatly in resolving cavities and occlusions, such as the handles of the 'Greek Vase' in Fig. 7 (bottom). The better quality is also reflected in the 3D print (see Fig. 6). For a 3D point to be reconstructed in the virtual model corresponding to the physical surface position, MVS requires at least three neighboring camera perspectives to cover the area around that point. This means that any occlusion and cavity can be resolved as long as all surface points within can be seen at least by three cameras, i.e. the direct line between a surface point and at least three cameras does not intersect other surface parts. Thus, the angular resolution of the camera arc required for successful reconstruction depends on the size of cavities of the object surface. There are also cases where cavities are oriented such that they can only be resolved in the other angular dimension, i.e. along the camera arc by at least three subsequent cameras, which are positioned at fixed angular intervals of 20°. If the object can not be reoriented to solve this problem, then the only solution is to increase the number of cameras, which is relatively easy due to the distributed network design: The control software flexibly allows for an arbitrary number of camera nodes, as long as they are reachable over Ethernet, and the cost does not significantly scale up in the number of additional cameras due to the low price of scanning nodes consisting of Raspberry Pi micro computer and camera each. Of course there are also cavities or surfaces positioned and/or oriented such that the MVS requirement can not be fulfilled by the hemispherical distribution of cameras, where the arc design alone has a drawback. The next version of the setup will be equipped with arcs covering a full sphere to cover this problem, and thus

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**Figure 7:** *Rendering of objects digitized in 3D by CultArc3D_mini.* ***Top****: 'Bust' from front, back and top perspective, exposing a deep cavity successfully reconstructed despite the relatively small image set captured (3D model based on 81 images captured in under 2 minutes).* ***Bottom:*** *'Greek Vase' rendered in texture and gray scale (3D model based on 297 images captured in under 4 minutes).*

will provide a homogeneous coverage of the object from all sides, both for 3D geometry and optical material behavior acquisition. Based on the relation between the camera resolution and the distance between camera and object surface, assuming an object measuring 50% of the maximum height and diameter, the current setup achieves a theoretical best measurement point (3D vertex) sampling distance of about 200 $\mu m$. Actual performance can be better for closer distances between camera and object surface and lower for difficult surface materials, such as very dark or shiny materials, or insufficient structure on the surface for identifying correspondences between neighboring camera perspectives. The printing accuracy reaches 100 $\mu m$ in the best case in the vertical dimension (layer thickness), which, however, requires significantly longer printing times. Since for photogrammetric reconstruction, diffuse lighting is required, additional environment light does not have a significant negative impact, as long as it is homogeneous (no spot light). The light situation during capturing is also included in the color calibration for all cameras (see Section 4.5), and must consequentially stay constant during the entire scan. The process of acquisition of optical material properties is more influenced by environment light, which is why it is advisable to cover the scanner using dark cloth, which can be accomplished by simply covering the entire plexiglass housing. The resulting 3D model is provided as .obj file including textures. Holes due to failure of reconstruction, for example in areas of difficult materials or cavities, are automatically closed by the photogrammetry solution up to a defined size. The underside of the object is typically larger than the threshold and remains open. During the slicing process, i.e. the preparation of the 3D model for printing, all remaining holes are closed, guaranteeing a watertight model.

### 5.2. Timing

The acquisition time for 3D geometry and texture is constant and object independent, but depends on the number of images captured, which is controlled by the angular step size $s$ chosen in the control software. Capturing all 9 cameras while rotating the camera (and light) arc to angles from $10^\circ$ to $170^\circ$ in steps of $s = 20^\circ$, $10^\circ$ or $5^\circ$ results in image sets of sizes $9 \cdot (\frac{170-10}{s} + 1) = 81$, 153 and 297 images, respectively (Fig. 3 shows the camera positions for $20^\circ$ steps). Reconstruction time depends on the software used, the hardware platform running the reconstruction (the more cores the merrier), the target quality chosen in the control software, and the complexity and size of the object. The latter aspect is due to optical flow which is applied to the image set in order to find visual correspondence points, or SIFT features, between neighboring perspectives, ultimately to extract depth information [GKA*10]. The larger the object (i.e., the more image area is covered by the object) and the stronger the surface structure, the more feature points are found in each image on the object surface, up to a predefined limit. The number of feature points in turn has a negative impact on computation time, but a potentially positive impact on reconstruction quality.

Table 1 summarizes image acquisition (top) and 3D reconstruction (middle) times for the three currently available acquisition modes for the object 'Greek Vase' shown in Fig. 6 and Fig. 7, as well as times for replication on two different 3D printers (bottom). Image acquisition times are constant and object independent as the capturing process follows a fixed routine which only depends on the

**Table 1:** *Runtime analysis for the three steps along the 3D replication process chain: 3D scan, 3D reconstruction and 3D print.*

| **3D Scan (Automatic Image Acquisition)** | | | |
|---|---|---|---|
| Device: | CultArc3D_mini | | |
| | Image Set (angular step size) / Time | | |
| Process Step | 81 ($20^\circ$ steps) | 153 ($10^\circ$ steps) | 297 ($5^\circ$ steps) |
| Object Feed-in [s] | 12 (0'12") | 12 (0'12") | 12 (0'12") |
| 3D Scan Process [s] | 116 (1'56") | 150 (2'30") | 231 (3'51") |
| Object Feed-out [s] | 14 (0'14") | 14 (0'14") | 14 (0'14") |
| **Photogrammetric 3D Reconstruction** | | | |
| Software: | Agisoft Photoscan (Setting 'High Quality') | | |
| Hardware Platform: | 2 x 18 Cores, 72 Threads (64 used), 512 GB RAM,<br>2 x GTX980 Graphics Card | | |
| | Image Set (angular step size) / Time | | |
| Process Step | 81 ($20^\circ$ steps) | 153 ($10^\circ$ steps) | 297 ($5^\circ$ steps) |
| Alignment [s] | 149 (2'29") | 501 (8'21") | 1125 (18'45") |
| Depth Reconstruction [s] | 76 (1'16") | 185 (3'05") | 3635 (60'35") |
| Mesh Reconstruction [s] | 26 (0'26") | 22 (0'22") | 25 (0'25") |
| Texture mapping [s] | 73 (1'13") | 86 (1'26") | 160 (2'40") |
| **3D Print** | | | |
| Object: | Greek Vase | | |
| 3D Printer / Filament | Extrusion / Printing Bed Temp. | Size (%) | Time |
| Ultimaker 2+ / white ABS 2.85$mm$ | $250^\circ C$ / $105^\circ C$ | 95% | 5h53'30" |
| Dremel 3D40 / black PLA 1.75$mm$ | $230^\circ C$ / not heated | 18% | 0h11'58" |

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angular step size. Feed-in and -out of the scanner over the conveyor system requires constant time. Photogrammetric 3D reconstruction time (Table 1, middle) is strongly dependent on the size of the image set, especially for the alignment process, where all images have to be compared against one another to identify feature pairs between neighboring perspectives and refine the positions and orientations of the single perspectives in a common coordinate system. During calibration we already specify a coarse alignment that is used as basis during alignment. Also, we optimize this step by predefining the local neighborhood of each capturing perspective, as these are known beforehand due to the system design. Depth reconstruction is strongly exponential in the number of images, as again all sets of neighboring image perspectives are considered to generate point clouds for each perspective. Mesh reconstruction is independent of the image set size as it runs on the resulting consolidated point cloud from the previous step. Finally, texture mapping tries to identify the best images from all perspectives to generate textures for all sides of the 3D model of the object and again depends on the image set size.

The time required for 3D printing (Table 1, bottom) is heavily affected by the target replica size, as well as the 3D printing resolution. Also, it is hard to give a clear dependence of the printing time in terms of the input parameters due to its dependence on several factors such as added structures inside the object for stability during slicing (transformation of the 3D data into a layer-wise representation understood by the 3D printer). A clear prognosis of the actual printing time depends on the printer model used and all input parameters, from the target object size over quality, filament and printing bed temperatures, to support structures and layout of internal auxiliary structures, and can be best provided by the printing software, which generates the final data for the 3D printer and thus has access to the full parameter set.

## 6. Conclusion and future work

We have created a fully automatic Zero-Button 3D Replicator that is close to a product, comes at low material cost, and allows for high throughput. In this way we have created the link between the two rapidly evolving domains of 3D scanning and 3D printing and demonstrated that the old dream of actually replicating objects is graspable. The system is designed in such a way that it is ready to acquire far more meaningful information than geometry and texture only, leading to highly realistic replicas concerning their material behavior, if recent 3D printing technology, both in hardware and software, is applied. This is an important step for the domain of Cultural Heritage, where millions of sensitive artifacts endangered by the effects of time, and increasingly by other negative influences as well, await 3D digitization, which at this scale only is possible with massive throughput rates and full automation. Also, many applications are waiting for solutions to 3D replication, not only in Cultural Heritage. The Zero-Button 3D Replicator is showcased in action at the 3IT Innovation Center for Immersive Imaging Technologies, Berlin, and can be visited on request. The demonstrator presented here is just the beginning, a first proof of concept for the 3D analog of 2D copiers. We see a number of important aspects to be improved and extended in future development:

- High-quality version with more image sensors at higher resolution and better quality.
- Further speed-up of scanning process.
- Full spherical acquisition around object, including object underside, especially for optical material behavior acquisition.
- Continuous illumination using special base functions for light encoding instead of discrete light sources for higher angular resolution, and LED lighting with more homogeneous spectral distribution for better compatibility with 3D printing gamut.
- Lenses with electronically adjustable zoom and focus for automatic adjustment to different object sizes and optimum focus, and additionally use of focus stacking for larger depth of field.
- Accuracy evaluation according to VDI/VDE 2634 norm part 3 (specifically concerned with photogrammetry) taking into account different positions within the entire scanning volume.

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