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Original article

Modeling a virtual robotic system for automated 3D digitization of cultural heritage artifacts

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ABSTRACT

Complete and detailed 3D scanning of cultural heritage artifacts is a still time-consuming process that requires skilled operators. Automating the digitization process is necessary to deal with the growing amount of artifacts available. It poses a challenging task because of the uniqueness and variety in size, shape and texture of these artifacts. Scanning devices have usually a limited focus or measurement volume and thus require precise positioning. We propose a robotic system for automated photogrammetric 3D reconstruction. It consists of a lightweight robotic arm with a mounted camera and a turntable for the artifact. In a virtual 3D environment, all relevant parts of the system are modeled and monitored. Here, camera views in position and orientation can be planned with respect to the depth of field of the camera, the size of the object and preferred coverage density. Given a desired view, solving inverse kinematics allows for collision-free and stable optimization of joint configurations and turntable rotation. We adopt the closed-loop inverse kinematics (CLIK) algorithm to solve the inverse kinematics on the basis of a particular definition of the orientation error. The design and parameters of the solver are described involving the option to shift the weighting between different parts of the objective function, such as precision or mechanical stability. We then use these kinematic solutions to perform the actual scanning of real objects. We conduct several tests with different kinds of objects showing reliable and sufficient results in positioning and safety. We present a visual comparison involving the real robotic system with its virtual environment demonstrating how view poses for different-sized objects are successfully planned, achieved and used for 3D reconstruction.

1. Introduction

The recent progress in 3D digitization of cultural heritage artifacts is motivated by various reasons. Among these, risk of complete and irrecoverable loss of cultural heritage due to destruction or decay, e.g. caused by catastrophes and wars, is perhaps the most critical one. Furthermore, the digital copy can support the preservation and restoration of the original objects by minimizing the physical interaction and enabling virtual planning.

However, even for smaller artifacts the process of complete and detailed 3D digitization can be tedious and time-consuming while requiring specific knowledge and skills. In view of the growing amount of objects eligible for scanning, automatizing the process becomes essential. The *CultLab3D* [1] digitization pipeline (Fig. 1) aims at automated and economical mass digitization in 3D comprising geometry, texture and even optical material properties. By deploying novel robotic and scanning technologies, human interaction with artifact and scanning devices is reduced to a minimum.

A similar approach can be found in automated industrial quality inspection using optical scanners. Those systems are usually specialized on a certain series of identical products and benefit from available CAD models for the scan planning and comparison [2].

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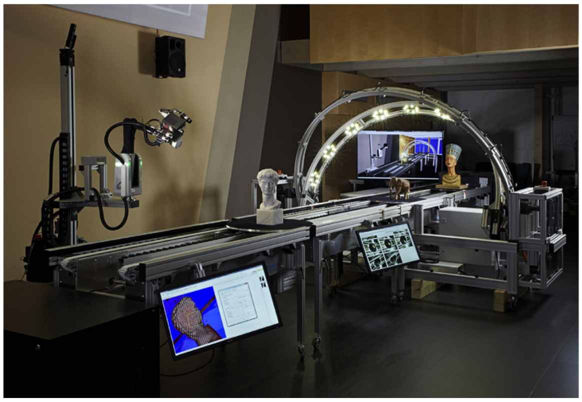

Fig. 1. An overview of the *CultLab3D* digitization pipeline [1]. Cultural heritage artifacts up to a maximum diameter of 60 cm are placed on conveyor belts and scanned at turntables with a 3D scanning camera and light arcs as well as with lightweight 3D scanning robot arms.

On the contrary, in the cultural heritage domain the unique objects come in a large variety regarding size, shape complexity and texture. This calls for a flexible scanning setup which is able to adapt itself to the objects of interest.

The *CultArm3D* module of *CultLab3D* system is such a flexible scanning setup, consisting of a flexible lightweight robotic arm with a mounted camera or scanner and a turntable for the object. The module is designed to position the scanning device and achieve various viewing angles to the object in order to complete surface coverage and resolve possible occlusions.

This paper addresses the problem of planning and achieving scan views with respect to the size of the object of interest, where the focus is on how the desired views translate to the robotic system. We therefore introduce an inverse kinematics solver that estimates the joint configurations and rotation angle. Thus, different viewing candidates can be evaluated and compared regarding their reachability, stability, safety and precision. After the inverse kinematics solver has found a solution, multiple theoretical solutions for the same view pose can be found since the structure of the manipulator is known. They create a set of available configurations which keep the camera view unaltered. The set of multiple configurations for a given scan view is then used to improve collision avoidance and stability of the manipulator. Several tests with different kinds of objects show reliable and sufficient results in positioning and safety. A visual comparison of the real robotic system with its virtual environment shows that view poses for different-sized objects are indeed successfully planned and achieved.

This paper is organized as follows. In Section 2, we describe the setup and environment of the robotic system followed by related work in Section 3. We then explain our approach in Section 4 and show experiments and results in Section 5. Finally, we describe conclusions and future work in Section 6.

2. Setup and environment

The *CultLab3D* digitization pipeline [1] is composed of hardware and software components; among these are conveyor belts and turntable, 3D scanning camera and light arcs as well as lightweight 3D scanning robot arms. The goal is to provide a 3D mass digitization solution for most cultural heritage artifacts up to a maximum diameter of 60 cm.

User interaction is limited to setting up target objects on carrier tablets, and picking them up again after acquisition. During the digitization process the artifacts move along a fully automated conveyor system and pass several scanning stations specialized for capturing certain visual object properties.

The basic photogrammetric configuration of the digitization pipeline consists of two scanning stations. At the first scanning station, a self-sufficient mechanism called *CultArc3D* captures geometry, texture and optical material properties using a motorized camera and light arc, featuring industrial, high-resolution video cameras. While *CultArc3D*'s advantage is the fast and parallel acquisition, it cannot resolve self-occlusions on complex-shaped objects, since its cameras and light sources are fixed at certain mounting points on rotary half-circular arcs. Thus, their motion and viewing positions are limited to a hemisphere with the object of interest in the center.

The aforementioned issue is addressed by the second scanning station called *CultArm3D* which is the scope of this article.

2.1. CultArm3D

Using the information of the 3D model draft obtained from the first scanning station, an iterative scan plan can be calculated to find a set of scan views to completely resolve the remaining uncertainties and self-occlusions in the final 3D model (Fig. 2)

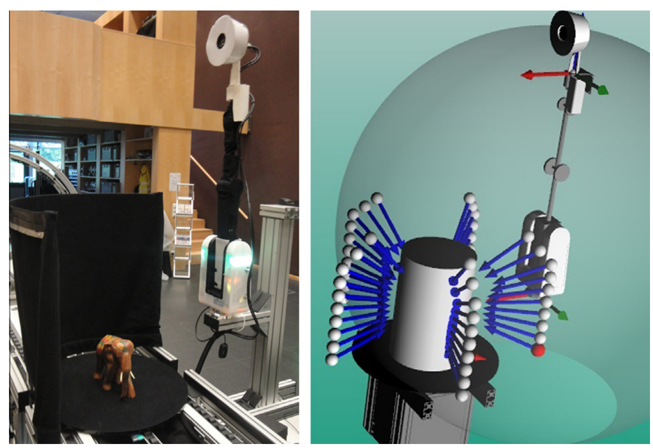

Fig. 2. Real and virtual setup of the *CultArm3D* module.

The *CultArm3D* module shown on Fig. 2 is designed to achieve these missing views in position and orientation. It combines a bionically inspired, lightweight robotic arm [3] focused on safety with a turntable for the object. The compliant robotic arm consists of 5 degrees of freedom (DOFs) with all rotational joints and can accurately move payloads up to 2 kg. The turntable is capable to precisely and smoothly rotate, clockwise and counterclockwise, around its vertical axis with infinite 360 degree rotations and is designed for object weights up to 50 kg. A high-resolution (10–20 mega pixels) camera together with a diffused white light source (LED ring) is mounted at the end of the robotic arm. The ability of the robotic system to achieve close-up views to the object, as well as the higher focal length of the camera lens allows for more detailed photography compared to the previous scanning station *CultArc3D*. Thus, even smaller and previously inaccessible features can contribute to the 3D reconstruction and locally enhance the model quality in coverage, geometry and texture resolution. However, complicated surfaces involving blank, shiny or translucent materials are problematic to captured with the current lighting setup and the standard photogrammetric 3D reconstruction process.