ECE 445

SENIOR DESIGN LABORATORY

PROJECT PROPOSAL

Image acquisition, 3D reconstruction and a visual interactive digital heritage system

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Team #9

CHUANRUI CHEN
(cc86@illinois.edu)
DENGLIN CHENG
(denglin3@illinois.edu)
QIANYAN SHEN
(qianyan2@illinois.edu)
ZIYING LI
(ziyingl4@illinois.edu)

Sponsors: Prof. Shurun Tan

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1 Introduction

1.1 Problem

Cultural artifacts possess significant historical, cultural, and artistic value. However, due to the passage of time and the impact of natural deterioration, many artifacts face risks of damage, loss, or decay. Additionally, for history enthusiasts and researchers worldwide, detailed information about specific artifacts is not readily accessible. Therefore, the conservation and exhibition methods of cultural relics have been a common concern of scholars around the world.

Traditional photographs often fail to capture the intricate details of artifacts, hampering comprehensive research and preservation efforts. Furthermore, the absence of user-friendly interactive interfaces limits the interaction between enthusiasts and artifacts, impeding immersive experiences in a virtual exploration of cultural heritage. Therefore, our team aims to develop a system that can generate realistic 3D models of cultural artifacts and provide users with a user-friendly interactive interface for immersive exploration.

By facilitating the digitalization of cultural heritage and sectors such as education, tourism, and grafting, our technology can generate greater economic benefits and serve as a solid theoretical foundation for the digital display, dissemination, and protection of historical relics.[1], [2]

1.2 Solution

We plan to design a system that can capture the detailed geometric shapes of artifacts using advanced scanning and 3D reconstruction techniques, and create 3D models. Additionally, we need to establish a database to store the collected artifact information and design a user-friendly interface that allows users to easily browse and interact. This will enable us to accurately capture and preserve the features of artifacts and provide a platform for enthusiasts to interact with artifacts up close.

Based on the analysis above, our first requirement is an accurate and efficient system for collecting the visual information of artifacts. We need to address how to handle the positional relationship between artifacts and cameras, as well as how to convert RGBD data into 3D models. Therefore, we need a mechanical device that can ensure the artifacts rotate at the desired speed while controlling the position and angle of the camera relative to the artifacts. This will help us obtain accurate RGBD data. Secondly, we need an efficient and accurate system to convert RGBD images into 3D models. We employ the point cloud reconstruction method, which involves converting RGBD images into point clouds, applying denoising and filtering operations to the point clouds, and finally reconstructing the processed point clouds to obtain a smooth 3D model.

However, considering our goal of better preserving, studying, and disseminating traditional cultural heritage, having only the 3D model data of artifacts is not enough. We also need to build a platform to store and render the models and provide interactive possibilities for users. We will export the reconstructed 3D models and load them into the database subsystem. Users can search for artifacts of interest in the database, and the rendered model data from the search results will be displayed in the interactive interface. Users can then appreciate and study the details of the artifacts up close through operations such as zooming and rotating.

1.3 Visual Aid

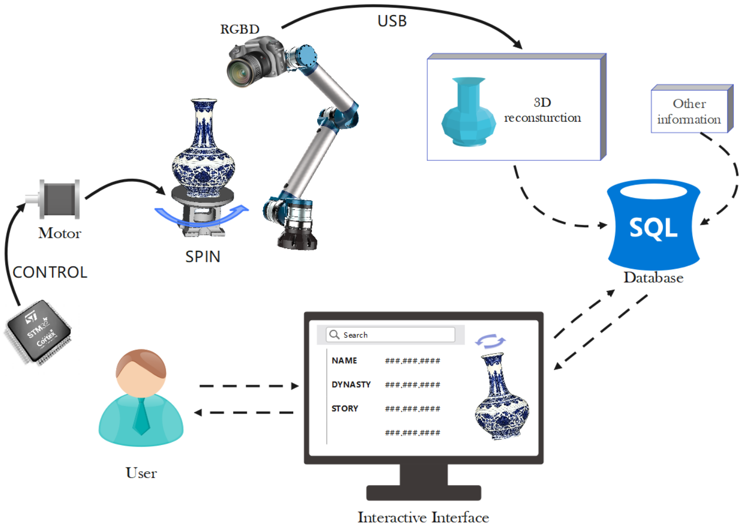

Figure 1: Visual Aid

1.4 High Level Requirements List

- **Modeling Outcomes:** We are capable of converting 920x1080 color images and 512x424 depth maps into point clouds. Our system can achieve the reconstruction of point clouds into 3D models. Additionally, we offer the ability to save and export the generated models in various formats.
- **User Interface and User Experience:** The database should store artifact information and 3D models accurately and securely. The system should execute the search and display the result page containing 3D reconstruction models and relevant information about the corresponding heritages within a response time of approximately 3 seconds. Users must be able to search for specific heritages by entering keywords in the search bar.
- **Hardware Level:** The High-level Requirements for the Hardware Aspect of the Project focus on ensuring robust functionality and performance across the entire system. Key goals include achieving a minimum response time of less than 200 milliseconds for real-time control, maintaining precise rotational control of the platform

with an accuracy of ±1 degree and a speed of up to 15 degrees per second for comprehensive artifact coverage, and attaining a scanning resolution of 10 millimeters for capturing detailed artifact features. These requirements are set to ensure that the system is both efficient in operation and capable of producing high-quality 3D scans, supported by seamless integration and communication between the power supply, control unit, sensor module, and mechanical components.

2 Design

2.1 Block Diagram

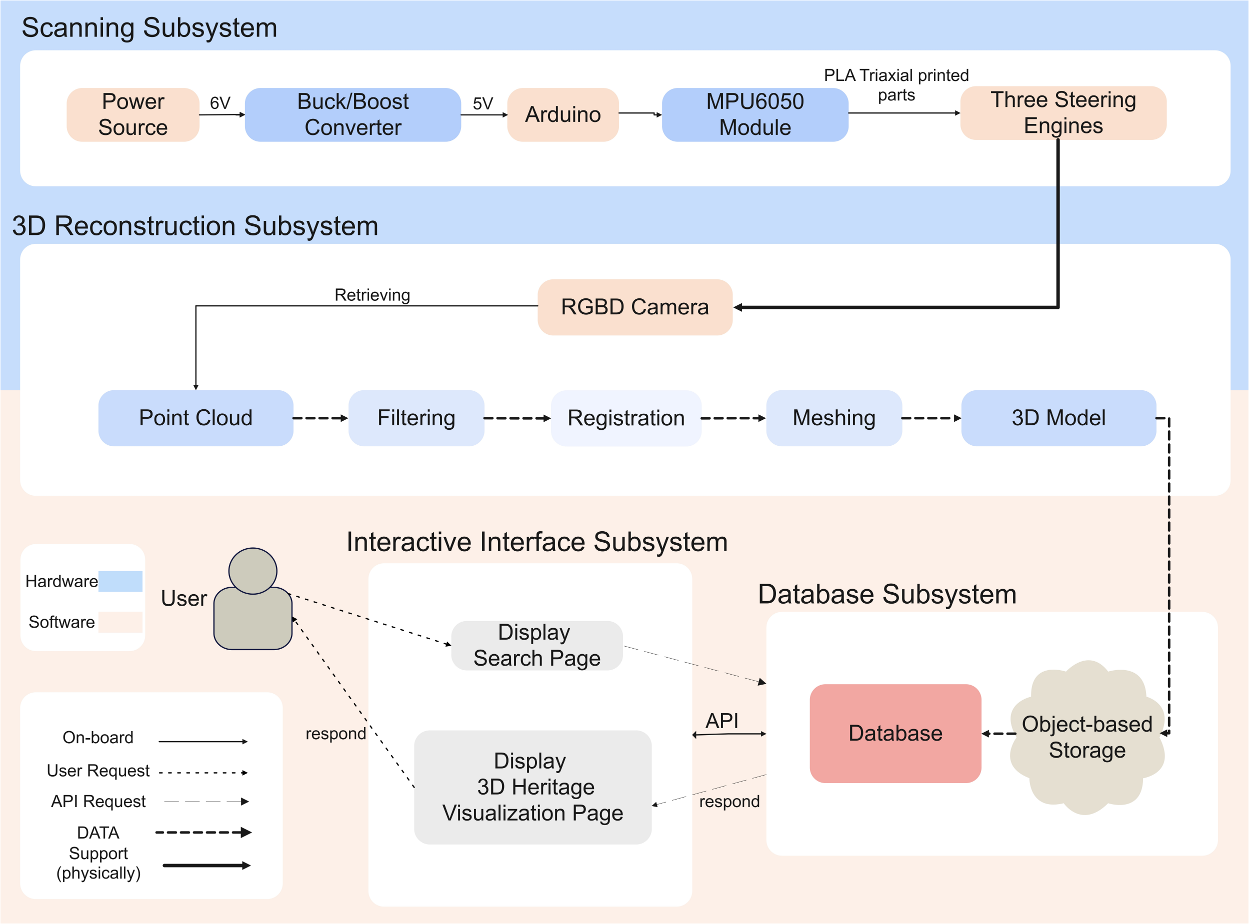

Figure 2: Block Diagram

2.2 Subsystem Overview

2.2.1 Scanning Subsystem

The Scanning Subsystem is designed to capture high-resolution, three-dimensional data of artifacts. It comprises a triaxial gimbal equipped with a RGBD camera for scanning and a rotational platform to hold and rotate the artifacts, combining an MPU6050 sensor for orientation data with PLA 3D-printed parts and servo motors for dynamic stabilization. The gimbal ensures precise control over the camera's position and orientation, allowing for detailed scans from multiple angles. The Scanning Subsystem enables the 3D Reconstruction Subsystem to capture data for model generation, ensuring accurate artifact digitization.

2.2.2 3D Reconstruction Subsystem

This subsystem aims to acquire point clouds through RGBD images and utilize them for 3D reconstruction. The system takes RGBD image inputs from the RGBD camera of the scanning subsystem. We need to convert the RGBD images of objects into point cloud data. After obtaining low-precision point clouds, the system needs to be able to perform point cloud denoising, remove outliers outside our targeted objects, and combine image features from different angles into the same point cloud. The reconstructed 3D models will be exported and stored in a database and presented to the user through an interactive interface.

2.2.3 Database Subsystem

This subsystem aims to store the basic information of the artifacts, including dynasties, historical backgrounds, stories, etc., and at the same time save the generated complex 3D model data. The data generated by the 3D Reconstruction Subsystem will be loaded into the Database Subsystem. With this database, users can search and view artifacts from exotic countries. When a user wants to retrieve an artifact, the database will find the corresponding information from its own stored data according to the search item entered by the user and display it through the Interactive Interface Subsystem for users to view artifacts from around the globe.

2.2.4 Interactive Interface Subsystem

This subsystem functions as the interface through which users can interact with the visual heritage system. Its main objectives include receiving user requests, providing feedback through a graphical user interface, and enhancing user experience through interactive features. By interpreting user search requests, the Interactive Interface Subsystem selects specific objects for querying, retrieves relevant data from the Database Subsystem, and then displays essential information along with rendering 3D models. The system further incorporates interactive control functions to make the user experience more interactive and deeply integrated into the exploration of cultural heritage, ensuring that they have a seamless and immersive experience.

2.3 Subsystem Requirements

2.3.1 Scanning Subsystem

This system consists of several small parts as follows: Power source and Buck/Boost converter; Arduino control part; MPU6050 Module; PLA Triaxial printed parts combined with three steering engines.

Power source and Buck/Boost converter: The power source, in conjunction with a Buck/ Boost Converter, is fundamental to providing a stable power supply that is crucial for the subsystem's operation. It ensures a continuous supply of $\mathbf{5V \pm 0.1V}$ and at least **500mA** to the Arduino and MPU6050 Module, which is essential for maintaining the system's performance and safeguarding the components with over-current and over-voltage protection.

Arduino control part: Serving as the central processing unit, the Arduino is tasked with interpreting the MPU6050's sensor data to manage the output signals to the PLA Triaxial Printed Parts and Three Steering Engine. This ensures the platform's orientation is adjusted in real time for optimal scanning accuracy. It operates efficiently with a stable 5V supply from the Buck/Boost Converter, processing data with minimal latency and managing communication through I2C protocol and PWM signals for precise control.

MPU6050 Module: This module is key to determining the platform's orientation by fusing accelerometer and gyroscope data. It interfaces directly with the Arduino, providing rapid data transmission to facilitate real-time orientation adjustments. The module's accuracy is paramount, requiring a stable power supply and fine-tuned sensitivity settings ($\pm \mathbf{2}$g for the accelerometer and $\mathbf{250}^{\circ}$/s for the gyroscope) to balance data accuracy and processing requirements, with minimal drift corrected via the Arduino.

PLA Triaxial printed parts combined with three steering engines: These components are crucial for the physical stabilization of the scanning platform, adjusting its orientation based on the data provided by the MPU6050 and controlled by the Arduino. The steering engines must respond swiftly to control signals, and the printed parts must be durable enough to support the necessary weight without compromising the system's ability to accurately adjust the orientation, ensuring the platform remains stable and level during scans.

2.3.2 3D Reconstruction Subsystem

The input to the subsystem from the scanning subsystem is a $\mathbf{920} * \mathbf{1080}$ color image and a $\mathbf{512} * \mathbf{424}$ depth image, and the subsystem will be able to acquire a point cloud from the input and obtain a point cloud of the corresponding angle through the image in less than **2s**.

The subsystem needs to filter the acquired point cloud data, retaining only the relevant parts related to objects while removing points outside the target range and outliers. Next, it performs registration of point cloud data from different angles to obtain a complete representation of the object's point cloud. It should also be capable of performing denoising to eliminate misaligned points.

Finally, the system should be able to select the most efficient algorithm to reconstruct objects and convert point clouds with magnitudes of **10,000** or higher into visually smooth 3D models. These models can be saved in **OBJ** and other formats for storage in a database and visualized through the interactive interface subsystem.

2.3.3 Database Subsystem

The main role of the Database Subsystem is storing artifact-related information. Specifically, the database subsystem needs to include an object-based storage to store the OBJ files generated by the Interactive Interface Subsystem. At the same time, it also needs to include a MySQL database, which is used to store the links to the corresponding OBJ files returned by the object-based storage as well as specific information about the artifacts.

In addition, the database subsystem needs to be able to support query functionality and return the queried data to the front-end, which is the Interactive Interface Subsystem, in about **1000ms**.

2.3.4 Interactive Interface Subsystem

The Interactive Interface Subsystem enhances the user experience by allowing users to search for heritages, view relevant information, and explore 3D models. For the graphic user interface, the subsystem interfaces with users through a search bar and interactive controls.

Users must be able to use a keyboard to search for specific heritages by typing keywords in the search bar. A result page containing a 3D model and relative information of this heritage must appear within **3 seconds** after a search. Clear and quantitative interfaces like API must be defined for communication with the Database Subsystem. It must provide interactive control functions allowing users to manipulate and explore the displayed three-dimensional models by mouse or touching the screen. It can turn back from the result page to the search page.

2.4 Tolerance Analysis

The hardware system is designed to ensure accurate and reliable 3D scanning, with a specific focus on maintaining a precision control within ±1 degree for orientation adjustments and a response time under 200 milliseconds to facilitate real-time processing. The system aims to achieve a minimum scanning resolution of 10 millimeters, allowing for detailed capture of artifacts and is optimized to complete a full 360-degree scan in under 5 minutes, ensuring both efficiency and quality in data collection. These requirements serve as a foundation for developing a robust and efficient hardware setup, capable of delivering high-quality 3D scans without compromise.

For the Tolerance Analysis, focusing on the gyroscopic drift in the MPU6050 sensor—a critical component in the scanning subsystem—poses a significant risk to the accuracy of the 3D models over time. The gyroscopic drift is the gradual error accumulation in the sensor's orientation data, which could lead to inaccuracies in the 3D reconstructed models if not properly addressed.

Mathematical Analysis and Solution:

Assuming the gyroscopic drift rate is approximately 0.01 degrees per second, over an extended scanning period of 5 minutes (300 seconds), the total potential drift could accumulate to 3 degrees. This deviation significantly exceeds the system's tolerance for precision control, which is within ±1 degree.

To mitigate this risk and demonstrate the component's feasibility within our design constraints, a complementary filter combines the gyroscope and accelerometer data. The accelerometer provides long-term stability but with slower response times, while the gyroscope offers quick responses with short-term precision. By applying a complementary filter with a ratio of 98 % gyroscope data and 2 % accelerometer data, we can effectively correct for gyroscopic drift while maintaining real-time responsiveness.

For example, if the gyroscopic data drifts by 3 degrees over 300 seconds, the accelerometer's stable but slow-response data can correct this drift, reducing the effective error in orientation to within the ±1-degree requirement. This application of sensor fusion via a complementary filter ensures that our system maintains its high-level requirement for precision control, thus making the design feasible despite the inherent risk posed by gyroscopic drift.

This analysis underscores the importance of integrating both gyroscopic and accelerometer data to overcome the limitations of individual sensors, ensuring the scanning subsystem meets its high-level accuracy and efficiency requirements.

3 Ethics and Safety

3.1 Ethics

In the development and implementation of our project, we face several ethical concerns that are integral to ensuring the integrity and societal value of our device. Given the cultural diversity of our potential user base, it is critical that we address the cultural sensitivities associated with the scents emitted by our hardware devices. Aligning with the IEEE Code of Ethics, particularly term 3, we commit to ”avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist” [3]. This commitment underlines our dedication to cultural respect and awareness, ensuring that our scent cues are designed to be non-offensive and appropriate across different cultural contexts. Moreover, we are mindful of the potential for misuse of emerging technologies, including our own, which can lead to unintended negative consequences. Therefore, we adhere to term 6 of the IEEE Code of Ethics, obliging us to ”maintain and improve our technical competence and to undertake technological tasks for others only if qualified by training or experience, or after full disclosure of pertinent limitations” [3]. This ensures that our technology is only distributed to organizations and companies holding valid and legal certifications, minimizing the risk of misuse.

Meanwhile, in line with ACM and IEEE ethics, we will maintain transparency in our operations and communications. As stipulated by the ACM Ethics guidelines, term 3, we will ” Be honest and trustworthy,”[4] providing full disclosure of system capabilities and limitations. Similarly, the IEEE Ethics guidelines, term 5, demands that we ” seek, accept, and offer honest criticism of technical work, to acknowledge and correct errors”[3] .

Furthermore, we are committed to fostering a positive and non-violent virtual environment, in adherence to the ACM Code of Ethics and Professional Conduct, which advocates against causing ”unjustified physical or mental injury, unjustified destruction or disclosure of information, and unjustified damage to property, reputation, and the environment” [4]. This principle guides us to exclude any violent or bloody scenes from our content, recognizing the potential harm they could inflict, particularly on children. Our ethical framework is not merely a set of guidelines but a core component of our project's philosophy and operational strategy.

Finally, by following both the IEEE Ethics guidelines [3] and ACM Ethics guidelines [4] , we aim to ensure that our technology not only advances in its technical capabilities but also contributes positively to society and operates within the highest standards of ethical conduct.

3.2 Safety

Ensuring the safety of both operators and subjects during the use of our 3D scanning system is paramount. We have identified several areas of focus to mitigate potential risks:

- Electrical Safety: Given our system's reliance on electronic components, we implement measures to prevent electrical shocks and hazards, ensuring all components are properly insulated and comply with relevant safety standards.

- Mechanical Safety: Our system includes moving parts; thus, we ensure these components are securely enclosed to prevent accidental injuries during operation.
- Environmental Safety: In our project's design and implementation, we consider the environmental sustainability and impact, respecting ACM's directive to " promote environmental sustainability,"[4]and IEEE's instruction to " strive to comply with ethical design and sustainable development practices"[3]. Therefore, the use of materials, such as lithium batteries, requires careful handling and disposal to prevent environmental harm. Utilizing biodegradable and recyclable PLA materials for 3D printed components, promoting sustainable and eco-friendly practices. We adhere to guidelines for the safe use and disposal of hazardous materials.
- Data Security: To protect sensitive information collected during scanning, we employ robust security measures to prevent data breaches and unauthorized access.
- User Training: Comprehensive training for all users is essential to safely operate the 3D scanner, emphasizing awareness of potential hazards and adherence to established safety protocols.

By addressing these ethical and safety concerns, our project aims to not only advance technological capabilities but also ensure our work benefits society responsibly and safely.

References

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[2] J. Sun and H. Kim, “Digital display design of historical relics—using artistic projection of historical relics as an example,” *TECHART: Journal of Arts and Imaging Science*, vol. 9, no. 1, pp. 35–48, 2022.

[3] IEEE. “IEEE Code of Ethics.” (2016), [Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html (visited on 03/07/2024).

[4] ACM. “ACM Code of Ethics and Professional Conduct.” (2018), [Online]. Available: https://www.acm.org/code-of-ethics (visited on 03/07/2024).