

PROJECT PROPOSAL

Voice-Controlled Robotic Study Assistant

Team # 46

Jiaxuan He (he59)

Qi Jin (qjin6)

Shuohan Fang (shuohan5)

Yicheng Chen (yc69)

Professor: Hua Chen

TA: Xihe Shao

March 23, 2026

Abstract

This proposal presents the design and verification of a voice-controlled robotic study assistant, engineered to provide hands-free interaction with physical reading materials for users with upper-limb motor impairments. The system accommodates standard academic documents ranging from ISO A5 to ISO A4 sizes, with a maximum binding thickness of 50 mm. The physical architecture features dual document workstations, allowing users to autonomously switch between multiple texts. A closed-loop robotic page-turning mechanism executes a three-step non-destructive sequence: actuated paperweights apply a 2.0 N to 5.0 N normal force to secure the document margins, a 15 mm silicone vacuum suction cup lifts the top page using a regulated 1.5 N to 3.0 N vertical force, and a 12 V NEMA 17 stepper motor sweeps the page 180 degrees across the binding within 4 seconds.

System control and user interaction are managed by a central Raspberry Pi microcontroller. The audio interface processes predefined natural language voice commands with a targeted response latency of under 3 seconds. An overhead camera provides closed-loop visual feedback to detect and recover from mechanical faults (e.g., multi-page pickups) and supplies page images for text extraction. Utilizing the PaddleOCR framework, the vision module extracts machine-readable text with an expected accuracy of $\geq 90\%$, which is subsequently processed by a text-to-speech (TTS) engine for audio playback. Power is distributed from a 12 V, 5 A main supply to dedicated 5 V and 3.3 V regulated rails to ensure thermal and electrical stability across all logic and electromechanical peripherals. Ultimately, the system targets a continuous operational success rate of $\geq 80\%$, providing a reliable, autonomous, and comprehensive assistive reading platform.

Content

- 1. Introduction 1
 - 1.1 Objective and Background..... 1
 - 1.2 High-Level Requirements 2
- 2. Design and Requirements..... 3
 - 2.1 Physical Design and Block Diagram 3
 - 2.2 Robotic Page-Turning Mechanism..... 4
 - 2.3 Adaptable Document Interface..... 6
 - 2.4 Power Module 7
 - 2.5 System Control and Integration..... 9
 - 2.6 Vision-Based Page Monitoring and OCR 11
 - 2.7 Voice Command and Audio Output..... 13
 - 2.8 Tolerance Analysis 13
- 3. Ethics and Safety 15
 - 3.1 Ethical Considerations..... 15
 - 3.2 Safety Concerns..... 15
- References 17
- Appendix A Requirement and Verification Tables 18

1. Introduction

This proposal outlines the design and verification of a voice-controlled robotic system engineered to physically manipulate reading materials. The system provides hands-free document access for individuals with upper-limb motor impairments. By integrating natural language processing, closed-loop electromechanical page-turning, computer vision, and text-to-speech (TTS) technologies, the device allows users to navigate and consume physical textbooks autonomously.

Rather than relying on pre-digitized media, this system specifically addresses academic or professional environments where instant digitization of printed documents is impractical. It eliminates the need for manual document conversion, providing a direct, real-time hardware interface for physical text manipulation.

1.1 Objective and Background

Users with upper-limb mobility limitations encounter significant physical barriers when studying from traditional bound textbooks, stapled lecture notes, and printed manuals. Although digital accessibility tools are prevalent, a vast majority of physical academic materials—especially those containing non-standard formatting, handwritten annotations, or mixed media—remain physically inaccessible without continuous human assistance.

The primary objective of this project is to engineer an autonomous, voice-actuated robotic assistant that restores independent physical reading capabilities. The system executes fundamental reading operations, including bidirectional page manipulation, autonomous switching between dual document workstations, and OCR-driven audio playback of the printed text.

To achieve these objectives, the proposed design synthesizes mechanical actuation, acoustic command processing, and optical feedback. A detailed technical breakdown of this proposed solution, accompanied by comprehensive mechanical renders, system block diagrams, and operational state machines, is thoroughly discussed in Chapter 2 (refer to Figures 2.1 through 2.8 for visual descriptions).

1.2 High-Level Requirements

The system must meet the following quantitative high-level functional and performance requirements to be considered successful:

1. **Voice Control and System Latency:** The central control module must accurately recognize and initiate the execution of predefined natural language voice commands (e.g., "next page," "previous page," "read page," "book one," and "book two") with a command recognition success rate of $\geq 80\%$ across 20 trials. The system must maintain a processing latency of ≤ 3 s from the completion of the user's speech to the initiation of the corresponding mechanical or software response.
2. **Mechanical Page-Turning and Paper Integrity:** The robotic manipulation mechanism must successfully separate and flip a single page forward or backward within 4 s per cycle, maintaining an operational success rate of $\geq 80\%$. To prevent multi-page pickups and physical damage, the vacuum suction cup must apply a strictly regulated vertical lifting force between 1.5 N and 3.0 N, ensuring it remains safely below the 5.0 N tearing threshold of standard 80 g/m² printing paper.
3. **Workstation Adaptability and Autonomous Switching:** The system must autonomously transition between two distinct document workstations without any manual intervention. The workstations and their respective actuated paperweights must dynamically accommodate document footprints ranging from ISO A5 (148 mm \times 210 mm) to ISO A4 (210 mm \times 297 mm) with varying binding thicknesses from 1 mm (e.g., stapled notes) up to 50 mm (e.g., bound textbooks).
4. **Vision-Based Closed-Loop Monitoring and OCR Accuracy:** The overhead optical character recognition (OCR) and vision subsystem must successfully capture page images, perform geometric dewarping, and extract machine-readable text with an end-to-end character accuracy rate of $\geq 90\%$. Additionally, the vision module must correctly verify mechanical page-turn completions or detect multi-page handling errors in at least 8 out of 10 trials to trigger automated reverse-sweep recovery sequences.

2. Design and Requirements

2.1 Physical Design and Block Diagram

The proposed voice-controlled robotic reading assistant comprises five primary subsystems: the central control unit, the power distribution module, the acoustic interface, the optical feedback and OCR subsystem, and the electromechanical page-turning mechanism. Figure 2.1 illustrates the high-level system block diagram and physical layout, detailing the power, data, and mechanical interfaces between these individual components.

Operationally, the system relies on centralized control architecture. Upon receiving a vocalized command via the microphone array, the central microcontroller processes the audio signal and dispatches the corresponding execution protocols. For navigation commands, the controller actuates the 12 V stepper motors and the vacuum pump to physically manipulate the printed document. Concurrently, the overhead optical sensor provides closed-loop feedback to verify mechanical success and detect fault conditions. For reading commands, the vision subsystem captures the page image for text extraction, which is subsequently relayed through the text-to-speech audio module.

Detailed quantitative specifications, alongside the complete Requirement and Verification (R&V) tables for each subsystem, are provided in Appendix A.

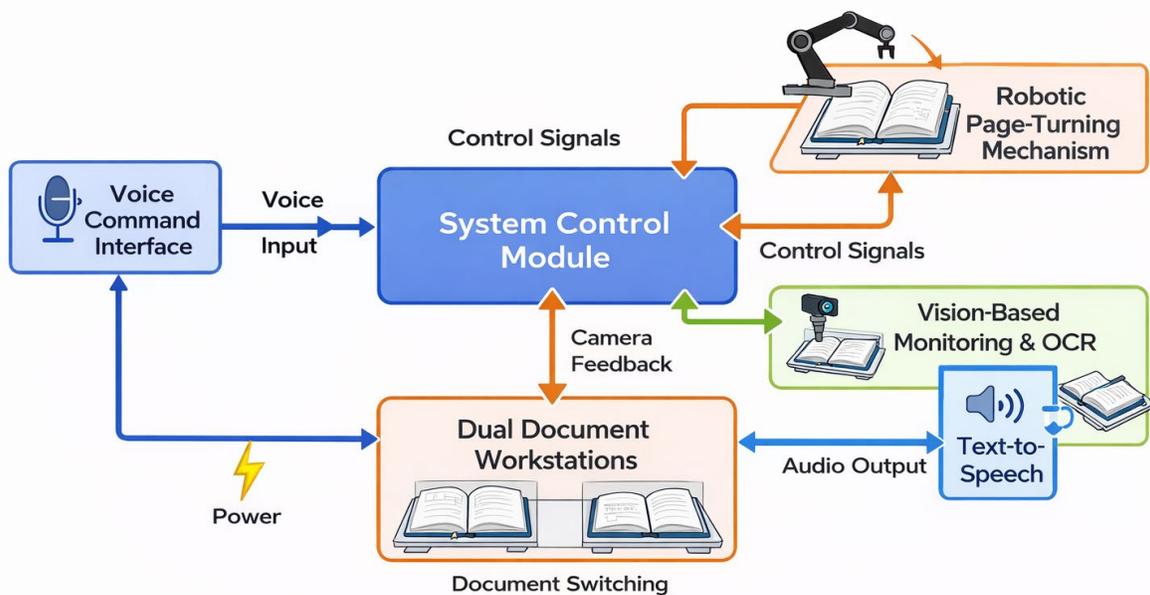


Figure 2.1 Page-Turning Robotic Assistant Block Diagram

2.2 Robotic Page-Turning Mechanism

The robotic page-turning mechanism executes the physical manipulation of the printed media. To accommodate various textbook sizes and binding types without causing damage, the system employs a coordinated three-step sequence. First, two actuated paperweights descend to secure the unlifted pages, applying approximately 2 N of downward force on both the left and right margins. Second, a vertically actuated robotic arm equipped with a 15 mm diameter silicone vacuum suction cup targets the bottom-center edge of the top sheet to initiate the lift. Third, a motorized swing arm rotates across the binding axis to push the lifted page to the opposite side. Figure 2.2 illustrates the spatial arrangement and physical integration of these actuators.

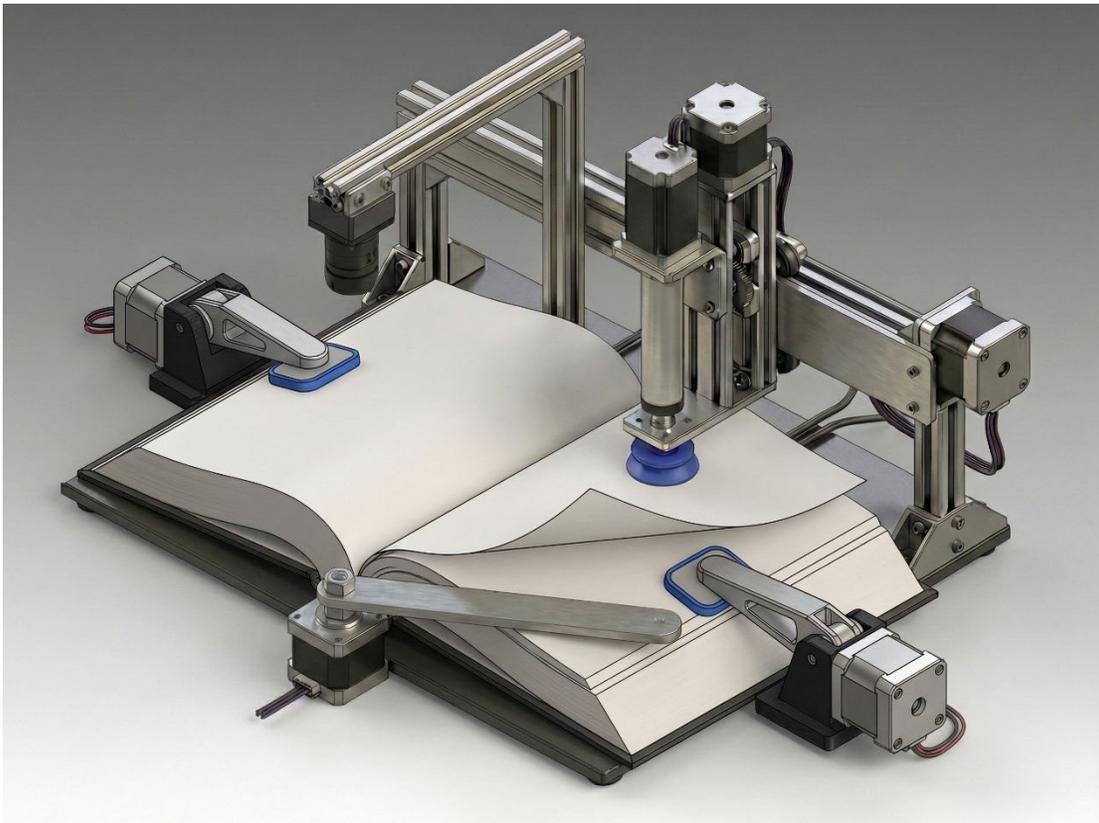


Figure 2.2 CAD Render of the Robotic Page-turning Mechanism and its Actuators

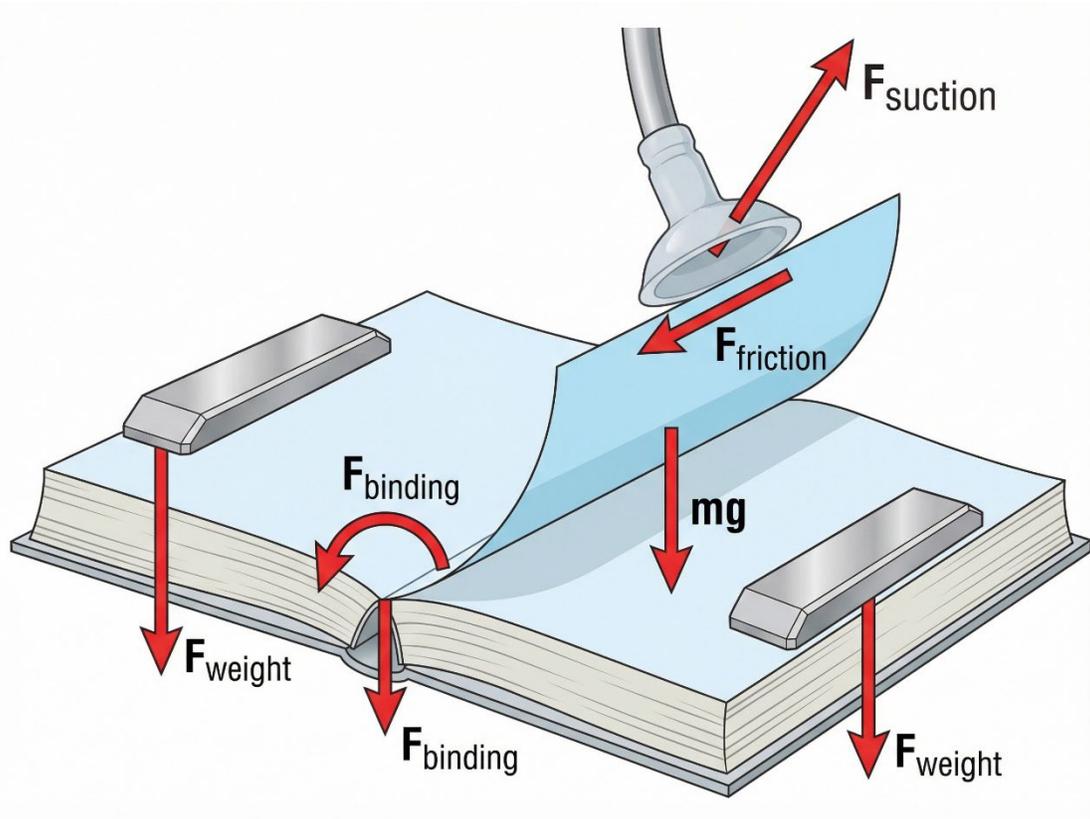


Figure 2.3 Free-body diagram of a single page during the suction lift phase.

To prevent multiple-page pickups and physical damage to the paper, the applied suction force must be precisely calibrated. Figure 2.3 depicts the free-body diagram of the top page during the initial lifting phase.

For a successful single-page lift, the vertical component of the suction force, $F_{suction}$, must exceed the sum of the opposing forces without exceeding the tensile limit of the paper. These opposing forces include the gravitational force on the page (mg), the vertical component of the static friction from the underlying page ($F_{friction}$), and the structural resistance at the book's binding ($F_{binding}$). This dynamic balance is defined in Equation (2.1):

$$F_{suction,y} > mg + F_{binding,y} + F_{friction,y} \quad (2.1)$$

where m is the mass of a single paper sheet, and g is the acceleration due to gravity. The suction force is generated by a 12 V DC micro vacuum pump and is governed by Equation (2.2):

$$F_{suction} = (P_{atm} - P_{vacuum})\pi r^2 \quad (2.2)$$

where P_{atm} is the ambient atmospheric pressure, P_{vacuum} is the absolute pressure within the suction system, and r is the effective radius of the suction cup (7.5 mm). Based on the mechanical properties of standard 80 g/m² commercial printing paper, the maximum allowable localized force before fiber deformation or tearing occurs is approximately 5 N [1]. Therefore, the central microcontroller utilizes pulse-width modulation (PWM) to regulate the vacuum pump, maintaining $F_{suction}$, strictly between 1.5 N and 3.0 N.

Once the suction cup elevates the page by a vertical clearance of 45 mm, the swing arm engages. The swing arm is driven by a NEMA 17 bipolar stepper motor. Operating at 12 V, this motor provides a holding torque of 0.4 N·m, which provides sufficient angular force to overcome the bending stress of the paper and complete the 180-degree sweep across the binding [2]. The specific requirements and step-by-step verification procedures for this mechanical subsystem are detailed in Table A.1 of Appendix A.

2.3 Adaptable Document Interface

The system must reliably process various forms of printed media, primarily thick bound textbooks and thin stapled lecture notes. Because these document types possess distinct physical profiles—varying in footprint, thickness, and structural tension—the central reading platform and its associated actuators require dynamic spatial adaptability.

The physical workstation is dimensioned to accommodate document footprints ranging from standard ISO A5 (148 mm by 210 mm) to ISO A4 (210 mm by 297 mm) [3]. To support comprehensive academic materials, the platform allows for a maximum binding thickness of 50 mm. Bound textbooks inherently exhibit significant page curvature and inward binding tension, whereas stapled notes lie flat but are susceptible to lateral shifting during the page-turning cycle.

To counteract these varying physical states, the two actuated paperweights are mounted on vertical linear guide rails, providing a total stroke length of 55 mm. This extended stroke allows the paperweights to descend and secure a thin 1 mm packet of notes or rest atop a 50 mm textbook. The paperweights are driven by micro-servos utilizing active current-sensing feedback to apply a consistent normal force between 2.0 N and 5.0 N on the lateral margins of the document. This specific force range provides sufficient pressure to flatten the natural curvature of a thick textbook spine, minimizing geometric distortion for the overhead optical character recognition (OCR) camera, while avoiding abrasive damage to standard 80 g/m² printing paper. Furthermore, the

contact pads of the paperweights are restricted to a width of 15 mm to ensure they secure the document without obscuring the text boundaries.

Similarly, the primary robotic page-turning arm incorporates dynamic Z-axis (vertical) compensation. Because the elevation of the top page changes depending on the document type and current page number, the stepper motor driving the vertical descent of the suction cup utilizes a pre-calibrated step sequence. This ensures the suction cup establishes a vacuum seal at an elevation of 50 mm for a fully opened textbook or descends completely to 1 mm for a flat stack of notes, preventing mechanical stalling and excessive downward force on the paper surface. For the complete quantitative requirements and mechanical verification steps regarding the dual workstations, refer to Table A.2 in Appendix A.

2.4 Power Module

The power module is responsible for receiving, stepping down, and distributing stable DC voltage from a standard 120 V AC mains supply to the corresponding 12 V, 5 V, and 3.3 V subsystems. As illustrated in Figure 2.4, the system receives an initial 12 V DC input via a 5 A AC-DC wall adapter.

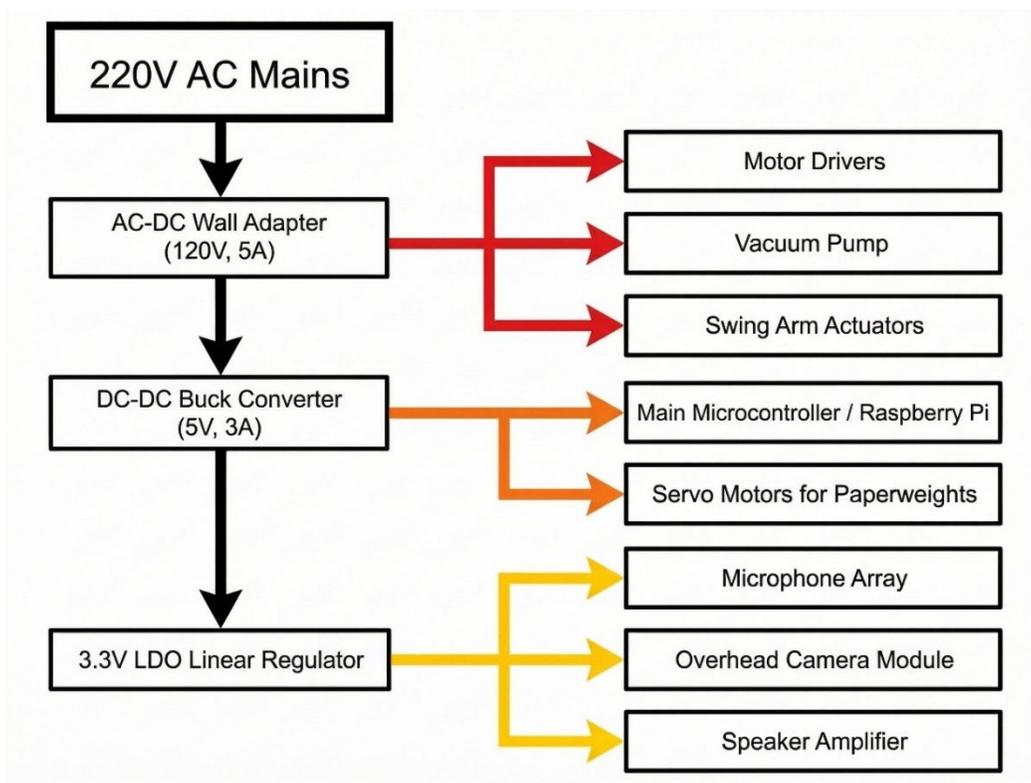


Figure 2.4 Power Distribution Tree Detailing the 12 V, 5 V, and 3.3 V Voltage Rails.

The 12 V rail directly supplies power to the high-power electromechanical components, which include the motor drivers for the NEMA 17 stepper motors, the DC vacuum pump, and the swing arm actuators. The theoretical peak current draw on the 12 V rail is estimated at 2.8 A during a simultaneous page-lift and swing-arm actuation event.

To power the logic controllers and intermediate-power peripherals, a DC-DC buck converter (e.g., LM2596) steps down the 12 V supply to a regulated 5 V rail capable of sourcing up to 3.0 A. This 5 V rail drives the main central processing unit (Raspberry Pi) and the micro-servo motors embedded in the mechanical paperweights. Because the voltage regulators must dissipate excess power as heat, thermal stability is a critical design constraint. The expected junction temperature T_J of the buck converter is calculated using Equation (2.3):

$$T_J = T_A + P_D \theta_{JA} \quad (2.3)$$

where T_A is the ambient temperature, P_D is the power dissipation, and θ_{JA} is the junction-to-ambient thermal resistance specified in the component datasheet [4].

Finally, a 3.3 V Low-Dropout (LDO) linear regulator steps down the 5 V supply to power the noise-sensitive logic and analog peripherals. These include the microphone array, the overhead camera module, and the speaker amplifier.

To ensure the selected voltage regulators maintain strict output regulation under continuous dynamic loads without excessive voltage ripple, the components will be evaluated using a custom constant-current test circuit, as depicted in Figure 2.5.

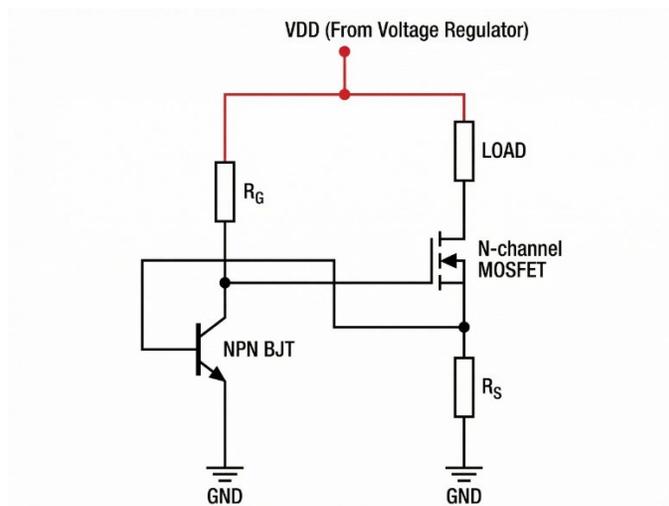


Figure 2.5 Constant-current Test Circuit for Verifying Voltage Regulator Load Stability

In this test configuration, the output of the voltage regulator is connected to the V_{DD} node. An N-channel MOSFET, biased by an NPN bipolar junction transistor (BJT), acts as an active electronic load. By adjusting the value of the sensing resistor R_S , the circuit sinks to a precise and constant current from the regulator, allowing for accurate empirical measurements of load regulation and thermal performance under maximum rated conditions. The detailed load stability requirements and verification procedures for the voltage regulators are outlined in Table A.3 of Appendix A.

2.5 System Control and Integration

Figure 2.6 illustrates the top-level state machine workflow that coordinates user interaction and page-turning operations. The overall system is modeled as a simplified state machine starting from the Initialization state. It transitions to the Idle state once all modules are successfully initialized. In the Idle state, the system waits for user voice commands and dispatches tasks accordingly.

Depending on the specific voice command, the system branches into different operational states. A “switch book” command triggers a transition to the Switch Book state, after which the system returns to Idle upon completion. Navigation commands such as “next page” and “previous page” lead to the Page Turn Forward and Page Turn Backward states, respectively, and return to Idle once the action is completed. Similarly, a “read page” command triggers the OCR state for text extraction, followed by the TTS Reading state for audio output, before successfully returning to Idle.

To ensure system reliability, error conditions that occur during workstation switching, mechanical page turning, or OCR processing cause an immediate transition to the Error Handling state. From this state, the system can either recover and return to Idle via a reset operation or transition to the Shutdown state in the case of critical hardware failures. This design ensures a clear, predictable control flow centered around the Idle state, providing unified handling of both user commands and unexpected system errors.

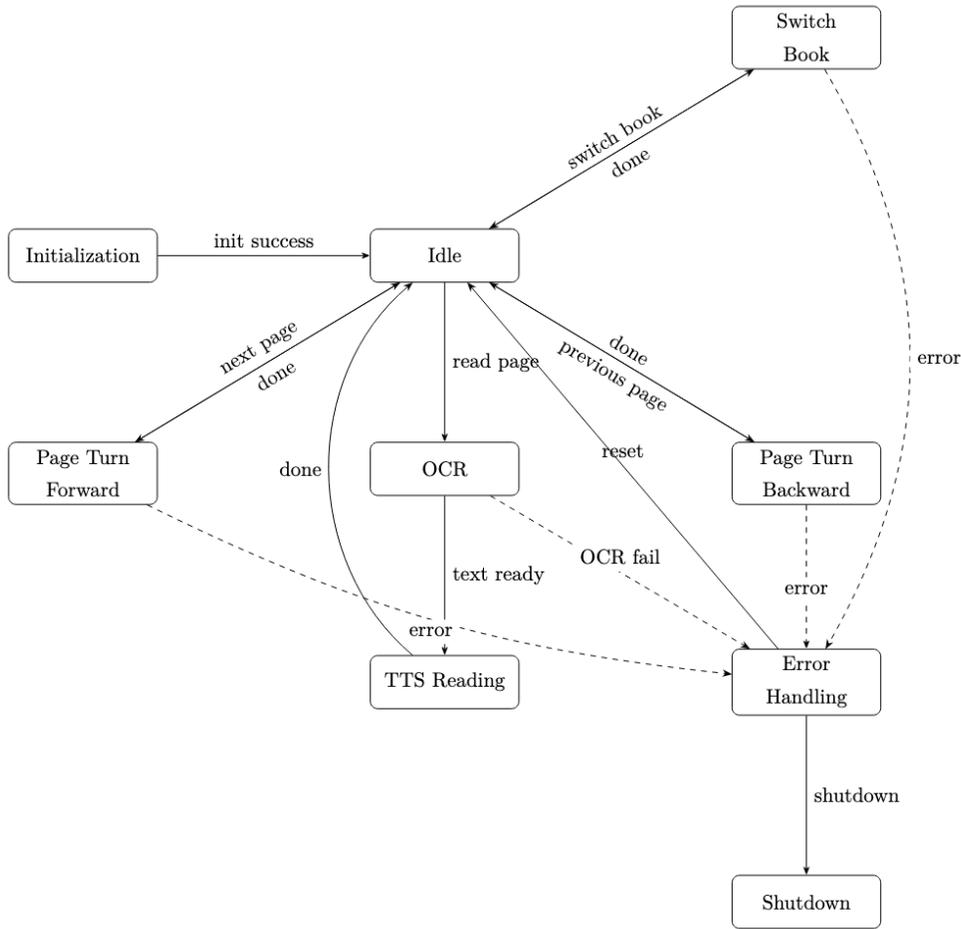


Figure 2.6 Top-Level State Machine Diagram for System Control and Integration

Moreover, Figure 2.7 illustrates the sub-state machine that models the core mechanical actions of a single page flip. The process begins in the Prepare State, where the system ensures that the page is ready for manipulation. It then transitions to the Align state, in which the system positions the suction cup at the edge of the target page.

Once aligned, the system enters the Suction state to activate the vacuum and attempt to pick up the page. If the suction is successful, the system proceeds to the Lift state, where the page is raised. This is followed by the Swing state to perform the flipping motion, and finally the Release state to place the page onto the other side of the document workstation.

In the event of a suction failure, the system transitions to the Fail state and performs a retry by returning to the alignment stage. This sub-state machine focuses on the most critical mechanical steps and isolates the primary failure point at the suction stage, enabling a simple yet effective control flow for reliable page turning.

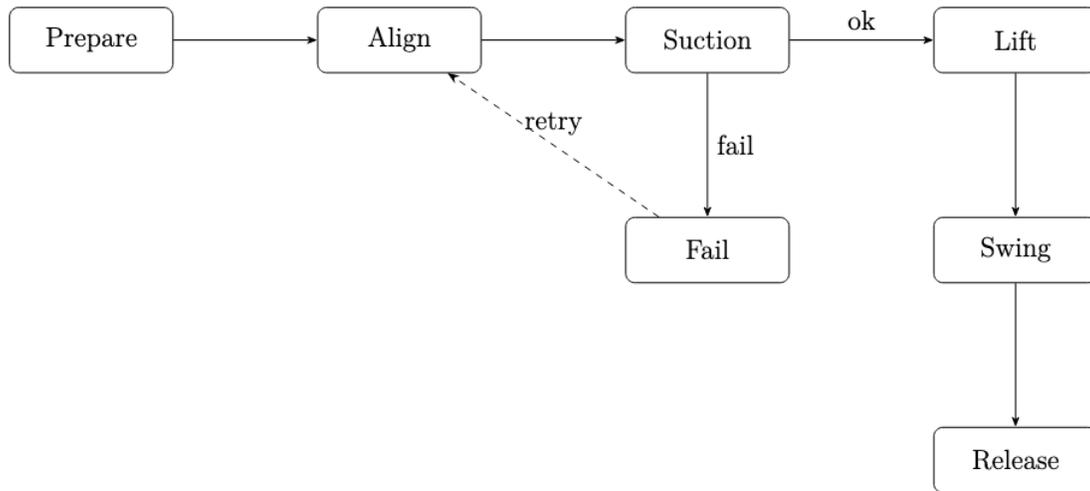


Figure 2.7 Sub-State Machine Diagram for the Mechanical Page-Turning Process

2.6 Vision-Based Page Monitoring and OCR

For the Optical Character Recognition (OCR) module, the system utilizes PaddleOCR, a mature open-source framework widely used for document image understanding. Once a page turn is completed or a voice command is received, the overhead camera captures the current page image. This captured image is first preprocessed to improve text visibility and recognition accuracy. The preprocessing pipeline includes grayscale conversion, page region cropping, contrast enhancement, and perspective correction, ensuring that the influence of page curvature, background noise, and camera viewing angles are minimized prior to text recognition.

The preprocessed page image is then sent to the PaddleOCR pipeline for text detection and recognition. In this design, the OCR module first locates the text regions on the page and then recognizes the printed content line by line, generating machine-readable text for downstream processing. Compared with a basic OCR-only approach, this two-stage pipeline is more suitable for book pages because it handles complex layouts, uneven text distribution, and partial geometric distortion caused by page flipping. Figure 2.8 demonstrates a preliminary test of the PaddleOCR engine accurately extracting printed text from a sample document.

After recognition, the extracted text is further post-processed to remove invalid symbols and obvious noise characters. Fragmented lines are merged into readable text blocks, and the final output is formatted into plain text. This processed text is delivered to the text-to-speech (TTS)

module for audio playback and to the keyword search module for content retrieval. Thus, the OCR subsystem serves as a critical bridge between visual page understanding and interactive reading functions. While Tesseract OCR was considered as a lighter-weight alternative, PaddleOCR was ultimately selected for this system because it provides a more modern, document-oriented pipeline and superior practical support for multilingual printed page recognition.

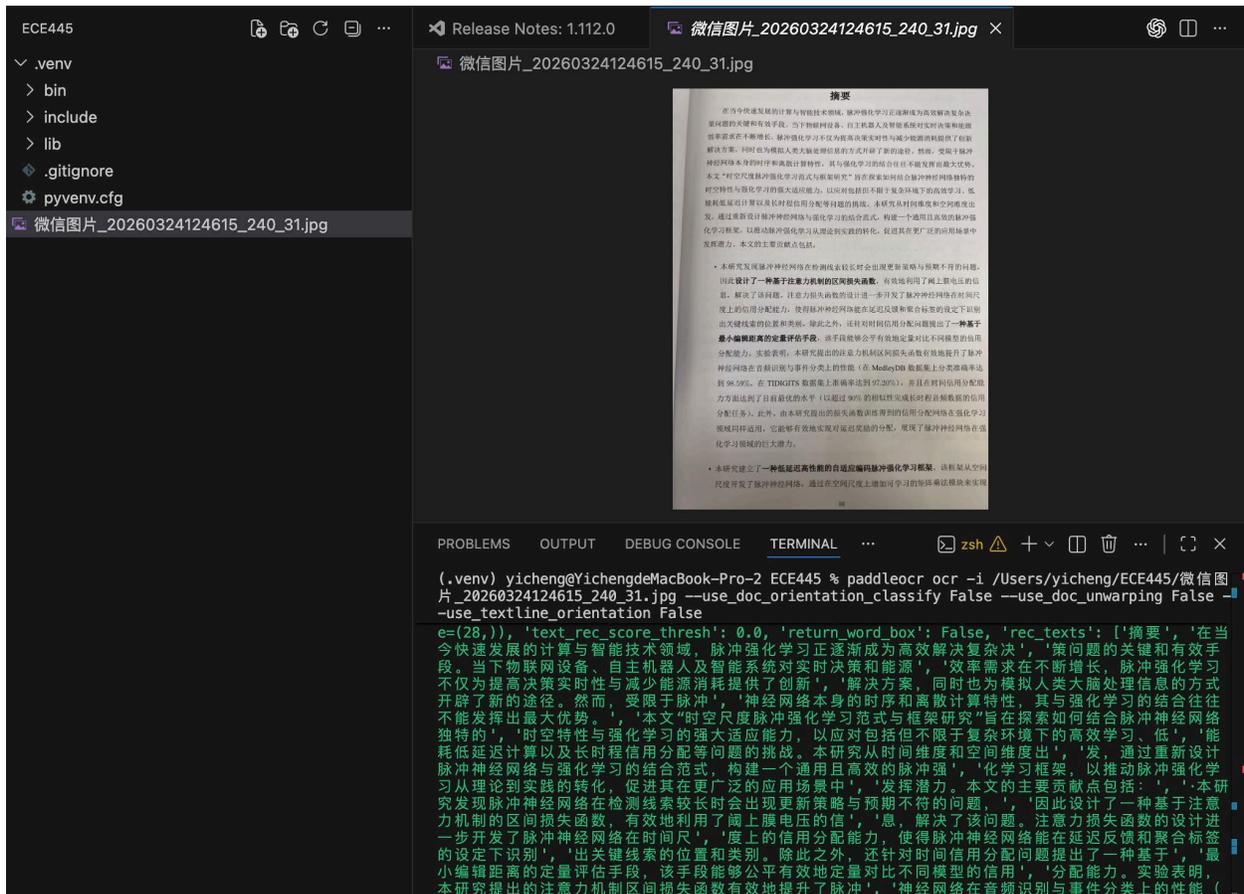


Figure 2.8 Example of Text Extraction Using the PaddleOCR Engine on a Printed Document

2.7 Voice Command and Audio Output

The speech recognition system in this work is implemented using an offline voice recognition module integrated with the main control board. The module includes an onboard microphone and performs real-time recognition of predefined voice commands without requiring an internet connection. Compared with cloud-based solutions, this approach provides lower latency, improved reliability, and eliminates dependency on network connectivity, making it suitable for embedded applications. We are considering using Voice Recognition V3 to achieve this.

The voice recognition module operates in a command-driven mode, where a fixed set of voice commands is predefined and trained in advance. In this system, typical commands include “next page,” “previous page,” “read page,” “switch book,” and “shutdown.” By limiting the recognition space to a small set of task-specific commands, the system significantly reduces ambiguity and improves recognition accuracy in practical environments.

The module communicates with the microcontroller through a UART interface. When a voice command is recognized, the module outputs a corresponding command ID, which is transmitted to the control unit. The control program continuously monitors the serial input and maps each received command ID to a specific system action. These actions are then used to trigger transitions in the top-level state machine. For example, a “next page” command activates the forward page-turning state, while a “read page” command initiates the OCR and text-to-speech pipeline.

To ensure robustness, a simple validation mechanism is implemented to filter invalid or unrecognized inputs. If the received command does not match any predefined instruction, the system ignores the input or requests the user to repeat the command. This mechanism prevents unintended operations caused by misrecognition.

2.8 Tolerance Analysis

The most critical tolerance issue in this design is reliable single-page pickup. If the suction force is too low, the top sheet will not separate from the stack or the book binding; if it is too high, multiple pages may be lifted, or the paper may crease or tear.

For the 15 mm diameter suction cup in Section 2.2, the effective contact area is $A = \pi(7.5 \text{ mm})^2 = 1.77 * 10^{-4} \text{ m}^2$, so the required force window of 1.5 N to 3.0 N corresponds to a pressure differential of approximately 8.5 kPa to 17.0 kPa. This pressure range is modest for a

miniature 12 V vacuum source and can therefore be regulated with pulse-width modulation around a nominal operating point. An 80 g/m² A4 page has a mass of roughly 5 g, so its gravitational load is only about 0.05 N [1], meaning that the dominant uncertainty comes from inter-page friction and binding resistance rather than page weight. A nominal suction force of about 2.2 N therefore leaves a margin of 0.7 N above the minimum lifting requirement while remaining 2.8 N below the conservative 5 N paper damage threshold for standard printing paper [1]. Likewise, the NEMA 17 swing actuator provides 0.4 N·m holding torque [2], which is significantly larger than the torque needed once a single page has been separated, so the dominant tolerance risk lies in pickup rather than transport.

Based on this analysis, the most critical tolerances are the suction-force regulation and the Z-axis contact position; the control system should maintain the effective suction force within approximately ± 0.5 N of its nominal value and the vertical contact error within approximately ± 2 mm to keep the mechanism inside a safe and reliable operating window.

3. Ethics and Safety

3.1 Ethical Considerations

Developing an assistive robotic platform for users with upper-limb motor impairments necessitates strict adherence to ethical principles regarding accessibility, technical honesty, and data privacy. In accordance with Section I, Item 1 of the IEEE Code of Ethics—"to hold paramount the safety, health, and welfare of the public"—the system design must prioritize the physical and emotional well-being of the user [5]. Furthermore, following Section I, Item 3 regarding the honest disclosure of claims, the team must strictly report verification data without exaggerating the system's capabilities. The device must not be marketed as a universal reading machine if it has only been validated on predefined 148 mm to 270 mm documents under optimal laboratory lighting conditions.

A project-specific ethical concern involves data privacy. Because the system integrates an open microphone array and an overhead camera, it inherently risks capturing sensitive user speech or private desktop environments. To mitigate this ethical risk and comply with privacy protection standards, all audio and optical data must be processed locally on the Raspberry Pi microcontroller. The system is designed to operate without transmitting raw image or voice data to external cloud servers, and all volatile memory buffers containing page images or speech queries will be overwritten immediately after the text-to-speech (TTS) execution is completed.

3.2 Safety Concerns

The primary safety hazards associated with this electromechanical system include mechanical pinch points, unintended robotic actuation, and electrical thermal overloads. The 55 mm vertical stroke of the actuated paperweights and the 180-degree sweep of the motorized swing arm introduce moving interfaces capable of trapping fingers or loose clothing. In compliance with the Occupational Safety and Health Administration (OSHA) standard 29 CFR 1910.212 for general machine guarding, hazardous motion envelopes must be physically isolated or heavily monitored to protect the operator [6].

Accordingly, the physical prototype incorporates an acrylic enclosure around the primary motor linkages and clearly demarcated keep-out zones on the document workstation. An accessible hardware emergency-stop (E-stop) button is integrated to instantaneously sever the 12 V power plane to all high-torque actuators. Electrically, while operating on regulated 12 V and 5 V DC

rails, stalled stepper motors can draw currents exceeding 1.5 A, creating localized heating and fire risks. To mitigate these electrical hazards, the power distribution module includes 3.0 A in-line fuses and active current-sensing limits on all actuator branches. During operation, the central controller is programmed to revert to a safe, de-energized Idle state upon detecting an OCR fault, a loss of optical feedback, or an unexpected motor stall, thereby ensuring user safety and preventing physical document damage.

References

- [1] J. A. Bristow and P. Kolseth, *Paper Structure and Properties*. New York, NY: Marcel Dekker, Inc., 1986.
- [2] NEMA 17 Stepper Motor Datasheet, Pololu Corporation, Las Vegas, NV, 2021. Available at: <https://www.pololu.com/file/0J714/SY42STH38-1684A.pdf>.
- [3] *Writing paper and certain classes of printed matter—Trimmed sizes—A and B series, and indication of machine direction*, ISO 216:2007, Int. Org. for Standardization, Geneva, Switzerland, 2007.
- [4] *LM2596 SIMPLE SWITCHER Power Converter 150-kHz 3-A Step-Down Voltage Regulator*, Texas Instruments, Dallas, TX, 2020. Available at: <https://www.ti.com/lit/ds/symlink/lm2596.pdf>.
- [5] IEEE Code of Ethics, IEEE Policies, IEEE, Piscataway, NJ, 2020. Available at: https://ewh.ieee.org/cmte/substations/posted_documents/ieee_codeofethics.pdf.
- [6] 1910.212 - General requirements for all machines, web page. Occupational Safety and Health Administration, Washington, DC. Available at: <https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.212>. Accessed March 2026.

Appendix A Requirement and Verification Tables

Table A.1 Robotic Page-Turning Mechanism

Requirements	Verification
<p>1. The suction mechanism must apply a lifting force between 1.5 N and 3.0 N to successfully separate a single sheet of paper without exceeding the 5.0 N deformation threshold.</p>	<p>1A. Connect a digital force gauge to the suction cup assembly.</p> <p>1B. Activate the vacuum pump at the designated PWM duty cycle.</p> <p>1C. Pull the force gauge vertically until the suction seal breaks and record the peak force reading to ensure it falls within the [1.5 N, 3.0 N] range.</p>
<p>2. The motorized swing arm must complete a full 180-degree page turn within 4 s.</p>	<p>2A. Place a standard 500-page bound textbook on the workstation.</p> <p>2B. Send the "next page" execution signal via the microcontroller.</p> <p>2C. Use a stopwatch to measure the elapsed time from the start of the swing arm's motion to its resting position on the opposite side. Verify $t \leq 4$ s.</p>
<p>3. The mechanism must successfully turn a single page forward and backward with an $\geq 80\%$ success rate over 20 continuous trials, causing no visible permanent damage (tears or creases) to the paper.</p>	<p>3A. Position the bound textbook on the workstation.</p> <p>3B. Execute 10 consecutive forward page turns followed by 10 backward page turns using the system's automated sequence.</p> <p>3C. After each turn, visually inspect the page under standard laboratory lighting (approx. 500 lx) for any tears, wrinkles, or permanent creases.</p> <p>3D. Record the number of successful, damage-free single-page turns. Calculate the success rate to ensure it is $\geq 80\%$.</p>

Table A.2 Adaptable Document Interface

Requirements	Verification
<p>1. The actuated paperweights must dynamically adjust to document thicknesses ranging from 1 mm to 50 mm, applying a normal holding force between 2.0 N and 5.0 N.</p>	<p>1A. Place a 1 mm stack of stapled paper on the workstation.</p> <p>1B. Command the paperweights to engage. Insert a thin-film force-sensing resistor (FSR) between the paperweight pad and the paper.</p> <p>1C. Read the analog output of the FSR using a multimeter and convert it to Newtons to ensure it falls within the [2.0 N, 5.0 N] range.</p> <p>1D. Repeat steps 1A through 1C using a 50 mm thick bound textbook to verify force consistency across the full 55 mm vertical stroke.</p>
<p>2. The workstation must accommodate ISO A5 to ISO A4 document footprints, ensuring the 15 mm paperweight pads secure the pages without exceeding a 20 mm margin from the outer edge.</p>	<p>2A. Center an ISO A4 document (210 mm by 297 mm) on the workstation.</p> <p>2B. Engage the paperweights and measure the inward intrusion from the physical edge of the paper using digital calipers.</p> <p>2C. Verify the intrusion distance is ≤ 20 mm.</p> <p>2D. Replace the A4 document with an ISO A5 document (148 mm by 210 mm) and repeat steps 2B and 2C to ensure the actuators can successfully reach and secure narrower margins.</p>
<p>3. The vertical (Z-axis) descent of the suction cup must successfully establish a vacuum seal on surface elevations ranging from 1 mm to 50 mm without causing the stepper motor to stall.</p>	<p>3A. Place a 1 mm document on the workstation and command the robotic arm to initiate a page lift.</p> <p>3B. Monitor the stepper motor current using an oscilloscope with a current probe. Verify the motor does not draw its maximum rated stall current (e.g., 1.5 A) upon contact.</p> <p>3C. Confirm visually that a successful vacuum seal is formed.</p> <p>3D. Repeat the procedure with a 50 mm thick book to verify successful seal formation at the higher elevation.</p>

Table A.3 Power Module

Requirements	Verification
<p>1. The 5 V DC-DC buck converter must maintain a stable output voltage of $5\text{ V} \pm 5\%$ (4.75 V to 5.25 V) with a voltage ripple of $\leq 50\text{ mV}$ under a continuous current load of up to 2.5 A.</p>	<p>1A. Connect the 5 V output of the buck converter to the V_{DD} node of the constant-current test circuit shown in Figure 2.5.</p> <p>1B. Adjust the sensing resistor R_S to sink a continuous load of 2.5 A, verified using a digital multimeter in series with the load.</p> <p>1C. Connect an oscilloscope across the V_{DD} and GND nodes. Verify that the DC voltage remains within the [4.75 V, 5.25 V] range and the peak-to-peak ripple does not exceed 50 mV.</p>
<p>2. The 3.3 V LDO linear regulator must provide $3.3\text{ V} \pm 5\%$ (3.135 V to 3.465 V) under a 1.0 A load and maintain a surface package temperature below 85 °C after 15 minutes of continuous operation.</p>	<p>2A. Connect the 3.3 V output of the LDO to the V_{DD} node of the constant-current test circuit.</p> <p>2B. Adjust R_S to sink 1.0 A of current.</p> <p>2C. Monitor the output with an oscilloscope to verify the voltage stays within the [3.135 V, 3.465 V] range.</p> <p>2D. Maintain the 1.0 A load for 15 continuous minutes. Use an infrared thermometer to measure the IC package surface temperature and verify it is $\leq 85\text{ }^\circ\text{C}$.</p>