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Design of an Open-Source Device for Immersion Staining of Cytological Samples

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Abstract *— This project details the design of a staining machine for processing samples in cytological tests for a clinical laboratory. The objective is to design a staining machine using local materials and components, ensuring a low manufacturing cost compared to commercial staining machines, and offering reliable staining through sequences programmable via a graphical interface. The designed device was based on a linear mechanism, in which the worktable consists of a separating base for cuvettes containing the chemical solutions for the stain. The samples are held in place by a basket, which adheres to the machine by means of electromagnets activated by the control system. Bipolar stepper motors were used for movement, activating a power screw mechanism. These motors were controlled using an Arduino Uno. Finally, an interface and a touchscreen were developed to allow execution of the staining sequences. Mechanical elements were selected according to local availability, achieving a competitive manufacturing cost.*

Keywords *— **Cytological tests, automation, Arduino Uno, staining machine, open-source device.***

I. INTRODUCTION

The staining of tissues is a fundamental tool for the identification, classification, and analysis of biological, chemical, and physical samples. In laboratory testing, staining is essential for highlighting specific structures, such as nuclei and fibers, allowing for their visualization and differentiation in tissues. It facilitates the identification and quantification of cellular components, which is crucial in histology and pathology.

In regional clinical laboratories in Córdoba, Veracruz, such as the San José laboratory, the staining process for cytological samples (specifically for Papanicolaou tests) continues to be performed manually. This practice presents limitations such as variability in staining quality and prolonged time consumption by technical personnel. While automated commercial machines exist, their high cost, specialized maintenance, and dependence on proprietary brands limit accessibility for small or low-budget laboratories. This project proposes an automated device based on open-source hardware principles to standardize the staining procedure, improving efficiency and reducing human error.

Objective

To develop an open-source device for the automation of the cytological sample staining process, adhering to NOM-241-SSA1-2021, NOM-014-SSA2-1994, and ISO 13485 standards for the San José laboratories in Córdoba, Veracruz.

Hypothesis

By integrating standardized mechanical components, locally available materials, and an open-source control platform (Arduino), it is possible to construct

an automated staining device that meets clinical quality standards while maintaining manufacturing costs below $6,000 USD.

Justification

Manual staining introduces high variability in results due to factors like reagent exposure time and operator intervention. Automation reduces processing time and significantly improves the reproducibility and quality of stained samples. Furthermore, the open-source hardware model fosters local innovation and technological appropriation, allowing health institutions to modify and scale solutions according to their specific needs. The standardization of processes also minimizes the risk of cross-contamination and improves biosafety in the handling of biological samples.

II. METODOLOGY

The development followed a five-phase mechatronic design methodology:

1. Selection of Alternatives: A decision matrix compared planar, rotational, and linear configurations. The linear configuration was selected (92% score) for its maintenance simplicity, energy efficiency, and local availability of components.

2. Conceptual and Detailed Design: The system was defined as a two-degree-of-freedom robot (X and Z axes).

X-axis: Linear transport across 6 storage spaces for reagents.

Z-axis: Vertical movement for sample immersion.

Effectors: An electromagnet system holds the slide basket for transport.

3. Mechanical Design:

Transmission: A 30mm diameter stainless steel power screw was selected for the X-axis to reduce wear compared to belt systems.

Motors: NEMA 14 stepper motors were chosen for their precision and local availability.

Containers: Borosilicate glass jars (Coplin style) were used for their resistance to acid, basic, and organic reagents.

4. Electronic and Control Design: The core of the system is an Arduino Uno paired with a TB6560 driver.

Sensors: Mechanical limit switches were integrated for machine calibration (homing).

User Interface: A touchscreen interface was developed to allow for the creation, editing, and execution of staining protocols.

Mechanical Component Technical Specifications

Component	Specification	Justification
Lead Screw	Stainless steel 304, Ø30 mm, 5 mm pitch	Corrosion resistance and linear motion precision
Stepper Motor	Bipolar NEMA 14, 1.8°/step, 0.4 Nm	Angular precision, sufficient torque, low cost
Linear Guides	Hardened steel with sealed bearings	Smooth motion, durability, low maintenance
Electromagnets	12 V DC, 50 N holding force	Secure gripping and electronically controlled release
Structural Frame	Stainless steel 316L profiles	Maximum resistance to acidic vapors and solvents
Reagent Containers	Borosilicate glass 3.3, 500 mL capacity	Optical transparency and chemical/thermal resistance

III. RESULTS

The device successfully executed complex staining sequences, such as the Papanicolaou protocol, with 100% repeatability in immersion times, completely eliminating human error in this critical variable. Each step of the protocol was executed with millisecond-level precision—an accuracy unattainable through manual techniques.

Repeatability testing involved executing the same protocol 50 consecutive times while measuring deviations in immersion time, reagent temperature, and sample positioning. The standard deviation in immersion times was less than 0.5 seconds, representing an improvement of over 100-fold compared to the manual method.

Repeatability Metrics

100% consistency in immersion times

< 0.5 s standard deviation

50+ cycles without variation

0 sequencing errors

Comparative Performance

Manual Method

Immersion time variation of ±30–60 seconds

Initial Prototype

Variation reduced to ±5 seconds

Optimized Version

Variation < 0.5 seconds — full precision

Biosafety Improvements

The automated enclosure and electromagnet-based end effector physically isolate samples from the operator, ensuring compliance with NOM-241-SSA1-2021. This physical separation dramatically reduces technician exposure to potentially carcinogenic reagent vapors such as hematoxylin, as well as organic solvents including xylene and alcohol.

Vapor Containment

A closed system with localized extraction captures approximately 95% of chemical vapors.

Minimized Contact

Technicians handle samples only at the beginning and end of the process.

Emergency Protocols

Emergency stop button and interlock-type safety locks are integrated into the system.

Additionally, the system includes spill detection sensors and an automatic shutdown protocol in the event of abnormal vapor levels. These safety features exceed minimum regulatory requirements, reflecting a strong commitment to occupational health.

Economic Impact: Confirmed Viability

The total construction cost remained below the USD $6,000 threshold, confirming economic feasibility for laboratories with limited budgets. This cost includes all mechanical, electronic, structural, and software components, representing approximately an 80% savings compared to equivalent commercial equipment.

Cost Breakdown

Mechanical components: USD $2,100

Electronics and control: USD $1,500

Structure and enclosure: USD $1,200

Interface and software: USD $600

Tools and consumables: USD $400

Return on Investment

For a laboratory processing approximately 100 samples per week, the investment is recovered in approximately eight months when accounting for technician time savings, error reduction, and reagent optimization. After this period, the system generates continuous net savings.

The construction and validation of the prototype yielded the following results:

Error Reduction: The device successfully executed repetitive immersion times and transitions, eliminating variability associated with manual operation.

Biosafety: The immersion mechanism isolated samples from the operator, reducing exposure to hazardous reagents like hematoxylin, eosin, and solvents.

Technical Efficiency: Calculations verified a system efficiency of 90%. The linear speed was determined to be 79.6 mm/s, ensuring efficient transitions without being overly abrupt.

Economic Viability: The use of local and standardized components ensured the cost remained competitive and accessible for regional laboratories.

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