



ING. MECATRÓNICA

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DISEÑO Y DESARROLLO DE UN SISTEMA ROBÓTICO PARA
MOVIMIENTOS DE CÁMARA AUTOMATIZADOS EN LA PRODUCCIÓN AUDIOVISUAL

DESIGN AND DEVELOPMENT OF A ROBOTIC SYSTEM FOR
AUTOMATED CAMERA MOVEMENTS IN AUDIOVISUAL PRODUCTION

Quito-2026

Aprobación del Tutor del Trabajo de Integración Curricular

Yo Félix Vladimir Bonilla Venegas, en calidad de tutor del Trabajo de Integración Curricular denominado: *DISEÑO Y DESARROLLO DE UN SISTEMA ROBÓTICO PARA MOVIMIENTOS DE CÁMARA AUTOMATIZADOS EN LA PRODUCCIÓN AUDIOVISUAL*, re-

alizado por Martín Roberto Aguirre Toapanta, ha sido orientado y revisado en todas sus partes y considero que cumple los requisitos establecidos por la institución. En virtud de ello doy mi aprobación a fin de continuar con el proceso académico correspondiente.



Félix Vladimir Bonilla Venegas

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A handwritten signature in black ink, appearing to read 'Martin Roberto Aguirre Toapanta', with a stylized, cursive script.

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Dedicatoria

Este trabajo, y todo el esfuerzo que representa, está dedicado a las siguientes personas. A mi familia, en especial a mi papá Roberto, mi mamá Paola y mi hermana Anahí, por ser mi apoyo incondicional y soportarme durante estos cinco años de carrera. Sin ustedes no habría sido capaz de seguir adelante. Las noches de desvelo, los viajes, los momentos en los que estuve ausente: hoy puedo decir que todo valió la pena. A todas las personas que me acompañaron en este camino. A Ángeles, por creer siempre en mí y ver mi potencial incluso cuando yo mismo no lo veía; siempre lo agradeceré. A mis amigos de la carrera, Ismael, Carlos, Adrián, Ochoa y Emi (elMijoGrupo) personas increíbles que tuve la fortuna de conocer, con quienes compartí noches de desvelo y desesperación, pero siempre saliendo adelante juntos. A mis amigos de toda la vida, Mecho, Nil, Mato, Villa, Celi y Juanjo, por ser mucho más que amigos: mis hermanos, que nunca me dejaron a pesar de todo. A las dos criaturas más nobles de este planeta, mis perritos Boster y Chiky, que pasaron incontables noches a mi lado mientras trabajaba en mis proyectos. A mi tía Milagros y a mi abuela, por apoyar mis ideas desde que era pequeño. Porque gracias a todos ustedes hoy soy la persona que soy, y no podría sentirme más afortunado de serlo.

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Resumen

La ejecución manual de movimientos de cámara en la producción audiovisual profesional introduce variabilidad entre tomas, fatiga del operador y costos operativos elevados que representan una barrera estructural para empresas productoras pequeñas y medianas. Este trabajo presenta el diseño, implementación y validación experimental del sistema ENA (Enfoque y Navegación Automatizado), una plataforma robótica de dos ejes de movimiento compacta que automatiza movimientos laterales y elevación tipo grúa para uso cinematográfico profesional. El sistema integra una transmisión lineal de tornillo de bolas accionada por un motor paso a paso NEMA 23 en el eje X, un actuador lineal DC en el eje Y, y una arquitectura de control inalámbrico dual ESP32 con retroalimentación de posición mediante encoder óptico de lazo cerrado. La validación experimental con tres configuraciones de carga demostró una desviación estándar de posición de 1.27 mm, frente a 27.6 mm obtenida por un operador manual, lo que significa que el sistema es aproximadamente 22 veces más consistente entre tomas. El sistema fue desplegado completamente en 8 minutos, cumpliendo el requisito de tiempo de configuración. Los resultados confirman que la plataforma ENA proporciona repetibilidad de trayectoria de nivel profesional a un costo accesible para entornos de producción pequeños.

Keywords: Sistema robótico de cámara, movimiento automatizado de cámara, transmisión por tornillo de bolas, control embebido ESP32, automatización de producción audiovisual.

Abstract

The manual execution of camera movements in professional audiovisual production introduces inter-take variability, operator fatigue, and elevated operational costs that represent a structural barrier for small and medium production companies. This work presents the design, implementation, and experimental validation of the ENA (Enfoque y Navegación Automatizado) system, a compact two-axis robotic camera platform that automates lateral and crane-style elevation movements for professional cinematographic applications. The system is made up of a ball screw linear transmission powered by a NEMA 23 (stepper motor) to accomplish movement on the X-axis. In the Y-axis, a DC linear actuator is used, along with a dual ESP32 wireless control architecture. For the closed loop, an optical encoder is used for feedback. Experimental tests for validation with 3 different camera configurations, as well as camera weights, demonstrates standard deviation of 1.27 mm, compared to 27.6 mm achieved by a manual operator. Proving consistency between takes, in contrast to manual operation. The system was fully deployed within 8 minutes, satisfying the operational setup requirement. The results confirm that the ENA platform provides professional-grade trajectory repeatability at an accessible cost for small production environments.

Keywords: Robotic camera system, automated camera motion, ball screw transmission, ESP32 embedded control, audiovisual production automation.

TABLE 1
ABET Criteria/Final Report Cross Reference Table

ABET Criterion Outcome	Target Level of Mastery	Best Examples with Section Numbers
1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Analyze	Sections 1.1, 2.3.2
2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors.	Create	Sections 1.3, 2.1, 2.3
3. An ability to communicate effectively with a range of audiences.	Apply	Sections 3.2
4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts.	Understand	Section 1.3
5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives.	Apply	Section 2.1
6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.	Evaluate	Sections 3.2, 3.3
7. An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.	Apply	Sections 2.3.6, 2.3.8

Source: Author's elaboration based on ABET guidelines and Bloom's Taxonomy.

Chapter I

Introduction

Problem Definition

A high degree of technical precision is demanded by the audiovisual production industry in the execution of camera movements. Shots involving lateral tracking, controlled panning, or vertical crane-style elevation must be executed with stability, smoothness, and exact repeatability, which is critical for multi-take workflows. Visual inconsistencies between shots are introduced when a given camera trajectory cannot be reproduced, extending post-production correction time and ultimately reducing the perceived quality of the final product.

Cranes, dolly systems on precision tracks and motorized gimbals are traditional mechanical solutions to this need. However, frequent limitations are shared among these tools; like, high costs, specialized operators and variability of human manual control. For small and medium audiovisual production companies, these limitations represent significant barriers.

During the requirements validation phase, quantitative evidence was found, where the stakeholders confirmed that the equipment required specialized operators and represents a significant time and production cost. Furthermore, the absence of automation dictates that any error in movement execution requires a completely new take, compounding both time and cost expenditures. Without an accessible robotic automation solution, a structural competitive disadvantage is faced by local production companies relative to larger studios equipped with industrial-grade systems. These limitations are addressed in this research through the design and implementation of the ENA (Enfoque y Navegación Automatizado) system, defined as a compact, programmable, two-axis robotic camera platform capable of executing precise and repeatable cinematographic movements at an accessible cost for small production environments.

State of the Art

The development of automated robotic systems for camera movement has been extensively investigated within the fields of robotics, control engineering, and computer vision.

Robotic Camera Systems and Autonomous Cinematography

The automated cinematography field is largely composed of research on vision-based tracking systems. The theoretical basis was established by combining computer vision and control, this

allowed for a system like a robot-mounted camera track to a moving target [1]. More advanced cinematography systems implement predictive control strategies that take into account physical restraints and cinematography rules to get coherent trajectories [2, 3]. The main limitation of this technology is that it uses aerial devices (UAVs) or large robotic arms used in industries, which are not practical and affordable for small-scale production businesses. UAV cameras have been shown to be effective in search and rescue missions [4], but due to their level of complexity, they cannot be used in a studio setting.

Motion Control and Trajectory Planning

The classical control approach, which is known as PID, still represents the standard of robotic cameras motion control because of its simplicity and efficiency [5,6]. The advanced approaches such as adaptive fuzzy control [7], finite-time convergence adaptive fuzzy control [6] and interval type-2 fuzzy logic [8] were used in the design of robotic manipulators to enhance tracking performance in terms of changing load conditions. In addition to that, the ideal techniques of trajectory planning based on interpolation and keyframe programming are mentioned as the best solutions to generate repeatable motions [2, 9]. Although the data-driven and neural networks approaches seem to be the future [10, 11], they presuppose large amounts of training data and resources that are not appropriate for limited hardware. [12]

Precision, Repeatability, and Mechanical Design

Precision and repeatability are identified as primary performance metrics in robotic camera systems [13, 14]. Robotic arms show high accuracy in positioning; nonetheless, the high cost and large size of the machines make them unsuitable for use in small studio spaces. It must be noted that within the mechatronic system design context, the inclusion of flexible mechanical components leads to the introduction of oscillations, which negatively affect image quality, making the adoption of a highly rigid ball screw mechanism in ENA over the belt drive an appropriate choice [15].

Embedded Systems and Cost-Effective Solutions

Nowadays robotic camera systems use embedded microcontrollers in order to provide real-time control of motors, sensors, and communication. It has been found out that processors like ESP32, for example, can handle the multi-axis movement algorithms well enough to allow for real-time operations [16, 17]. The research on stabilization of video footage in limited budget systems shows that high-quality motion can be performed with non-industrial components by choosing proper mechanics and algorithms [18]. Such commercial solutions as Mark Roberts

Motion Control (MRMC) system [19] and Motorized Precision MP Studio [20] are examples of high-end systems. However, although technologically advanced, those systems are too expensive for small production facilities.

Comparative Summary and Research Gaps

The principal categories of robotic camera systems are summarized in Table 2 . This provides a technical comparison of the different structural methods used in the industry. A significant research gap exists when it comes to solutions that use open hardware structures and sub-industrial pricing while sustaining high structural payloads. The ENA system is explicitly positioned to address this identified gap.

TABLE 2
Comparison of Existing Robotic Camera System Approaches

Approach	Important Work	Strengths	Limitations Relative to ENA Scope
Industrial Robotic Arm	KUKA CineRobotics [2]	High precision, multi-axis	Cost-prohibitive; not portable.
UAV / Aerial Platform	Goodrich et al. [4]	Unrestricted mobility	Regulatory constraints; unsuitable indoors.
Commercial Slider Systems	MRMC [19], Motorized Precision [20]	Purpose-built, reliable	Proprietary; high cost; no open customization.
Vision-Based Tracking	Papanikolopoulos & Kanade [1]	Autonomous subject tracking	Requires high-performance compute; complex setup.
ENA (This Work)	—	Low cost; compact; programmable; open hardware	Ground-based; 2 DOF; payload ≤ 20 kg.

Justification

There are three main justifications for the implementation of the ENA system: industrial necessity, academic value, and social benefit.

From the point of view of the industry, the audiovisual industry relies heavily on manually operated machinery which is both expensive and inconsistent in its operations. Using a programmable robotic camera system will provide a direct efficiency increase in production through removing variability in camera performance between takes, reducing set up times to less than ten minutes, and allowing for complex multi-axis camera movements to be performed by one person without any physical labor.

Academically speaking, the project utilizes three basic fields of Mechatronics Engineering: mechanical engineering (structural analysis of the ball screw and jib under 17 kg dynamic loads), electrical engineering (ESP32 dual-node system, H-bridge driving circuitry, and encoders for closed-loop feedback), and control engineering (PID trajectory control, motion profiling and autonomous homing).

Socially speaking, this project provides equal access to professional cinematography equipment. Through providing a cost-effective and open-architecture system, upcoming filmmakers and small production houses can create professional-quality material, increasing the competitiveness of their local market.

Objectives

General Objective

To design and implement a programmable robotic system, designated as the ENA platform, that automates camera movements in audiovisual productions, ensuring positional precision, trajectory repeatability, and a measurable reduction in production setup time.

Specific Objectives

- To design the mechanical structure of the ENA system to safely support and balance a payload of up to 20 kg, incorporating a ball screw linear transmission on the X-axis and a jib-actuator assembly on the Y-axis.
- To select and integrate the control system hardware (ESP32 microcontrollers, DM542T stepper driver, L298N H-bridge, and optical encoder) and develop the firmware required for two-axis coordinated motion.
- To implement pre-programmed cinematographic trajectories, including lateral tracking, panning, and crane-style elevation, featuring an autonomous homing sequence for repeatable point-of-origin calibration.
- To develop an intuitive human-machine interface (HMI) enabling operators to configure movement parameters, define A/B trajectory points, and execute automated shots with a setup time not exceeding ten minutes.
- To validate the performance of the prototype in representative audiovisual production scenarios by measuring positional accuracy, motion smoothness, and inter-take repeatability against defined acceptance criteria.

Chapter II

Methodology and Design

Requirements

The Enfoque y Navegación Automatizado (ENA) robotic platform has operational and structural qualities that were established within the initial conversation with the stakeholders. Below are the operational context and justification for each requirement, while the specific, measurable acceptance criteria are consolidated in Table 3.

Functional Requirements

The functional requirements state the main capabilities that the ENA system must have to automate cinematographic tasks effectively:

- **Trajectory Execution:** The system must perform calculated movements across the X (lateral) and Y (elevation) axes.
- **Setpoint Programming:** To ensure repeatability between takes, the platform requires a programmable A/B setpoint memory system accessed through the HMI.
- **Homing Sequence:** A stable mechanical origin must be established before any operation to keep accuracy and prevent mechanical collisions.
- **Predefined Modes:** The firmware must include standard motion modes to reduce configuration time for the operator on set.
- **Payload Accommodation:** The structure and actuation subsystems must safely carry the equipment, including the camera body, lenses, and accessories.

Non-Functional Requirements

These requirements state the system's operational quality, making sure it meets professional film industry standards:

- **Precision and Repeatability:** Motion must be smooth, any mechanical vibration translates to the camera recording.
- **Usability:** The human-machine interface (HMI) must be intuitive, allowing for easy setup and calibration to avoid delaying production schedules.
- **Portability:** The physical form factor must be compact and lightweight enough to transport and locate the gear across diverse locations.
- **Reliability:** The architecture must support continuous operation during extended filming

without hardware failures.

Constraints

The boundaries and development scope are defined by the following limitations:

- **Economic:** Solutions must align with commercial components to maintain the stakeholders budget viability and ensure maintainability.
- **Physical:** The architectural structure is constrained only to a minimalistic slider and jib arrangement.
- **Software:** The use of post-production software and other such editing tools is avoided, and only real-time hardware control is considered.

TABLE 3
System Requirements and Acceptance Criteria Matrix

Category	Requirement Focus	Metric / Acceptance Criterion
Functional	Automated multi-axis trajectory	Successful execution of 3 distinct shot types.
Functional	Autonomous calibration	Origin established within ± 1 mm.
Non-Functional	Operational setup time	Total configuration time < 10 minutes.
Non-Functional	Structural payload capacity	Maximum support of 20 kg load.
Non-Functional	Dynamic motion stabilization	Zero visible image artifacts at 24 fps.
Constraint	Component procurement	Exclusive utilization of COTS parts.

Table 3, which contains the collected data, represents the engineering benchmark for proving the performance of the prototype throughout its experimental test stages.

Conceptual Design

This project was approached using the VDI 2206 mechatronics design approach, where the design procedure is based on a systematic development from user requirements to the integration of a physical system. The system architecture was developed based on the closed-loop control concept, with the architecture consisting of four subsystems: User Interface, Control Logic Unit, Actuation Layer, and Feedback Layer.

The flow of the control signals in the sequence is described in Figure 1, where the control signals relating to the user commands for velocity, distance, and A/B points are received by the User Interface and then transferred wirelessly using the ESP-NOW protocol to the Con-

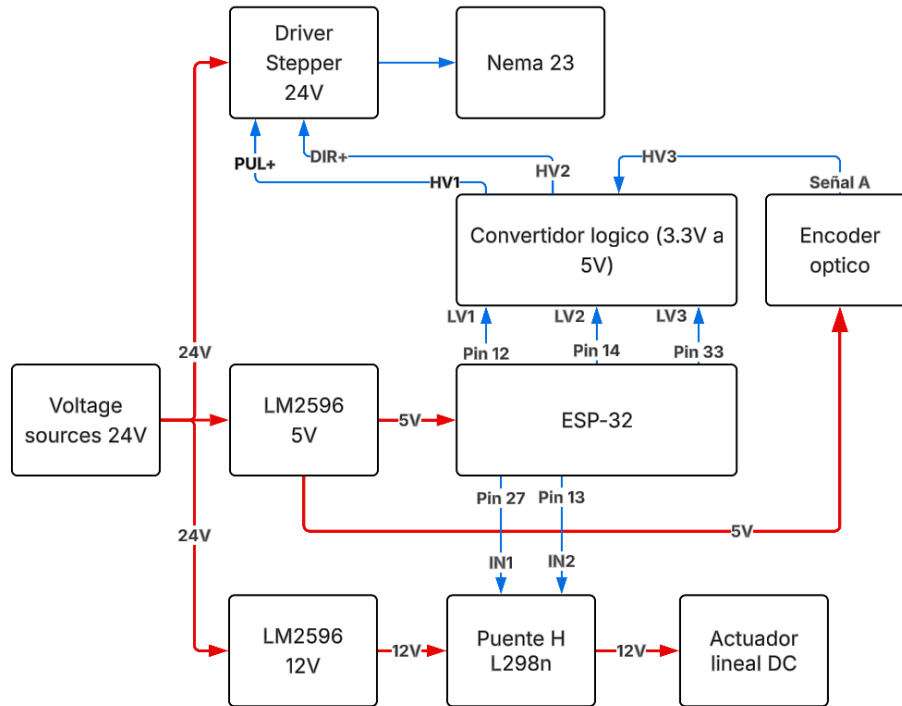


Fig. 1. ENA System Electronic Architecture and Power Distribution Diagram

trol Logic Unit. Here, the control signals are processed to form trapezoidal speed profiles and PID correction signals. The actuation layer transforms these signals into physical displacement along the axes. The feedback layer is responsible for the measurement of mechanical displacement and the provision of quadrature pulse signals.

As part of the conceptual design process, the following two mechanical transmission systems were considered for use as the main lateral navigation axis (X-Axis). Alternative A was a Ball Screw plus a Stepper Motor and alternative B was a Timing Belt plus a Precision Motor. The comparative matrix that formed the basis of the decision-making process in terms of load capacity, positioning accuracy, backlash, and vibration transfer is presented in Table 4.

Since the choice has been made through the qualitative criteria in Table 4, Alternative A was chosen. The large axial stiffness and low backlash of the ball screw are crucial for reducing low-frequency mechanical vibrations. The elasticity that is inherent in the timing belt under 17 kg loading makes it too risky to have any jitters and distorted images during the acceleration phases.

TABLE 4
Comparative Transmission Evaluation Matrix for the Primary Axis

Criterion	Alternative A: Ball Screw + Stepper	Alternative B: Timing Belt + Motor
Load Capacity	High axial rigidity; zero slippage under load.	Limited; susceptible to stretching under mass.
Positional Precision	Excellent; thread pitch provides fine resolution.	Moderate; affected by belt elongation over time.
Backlash	Minimal due to ball bearing preloading.	Moderate due to tooth pitch compliance and wear.
Vibration	Very low high-frequency dampening.	High risk of low-frequency oscillations.
Cost / Availability	Accessible; standard commercial components.	Variable; high specialization costs for high loads.
Selection	✓ Selected	—

Detailed Design

Mechanical Subsystem Architecture

Component Selection and CAD Modelling. The process of mechanical design began with the review of technical data and commercially available linear motion gear appropriate for the load and accuracy requirements of the ENA system. After choosing an appropriate series of components, the dimensions of each part was taken and accurately recreated using CAD tools, creating the assembly in which all custom parts were designed. Figure 2 shows the complete CAD assembly of the ENA system.

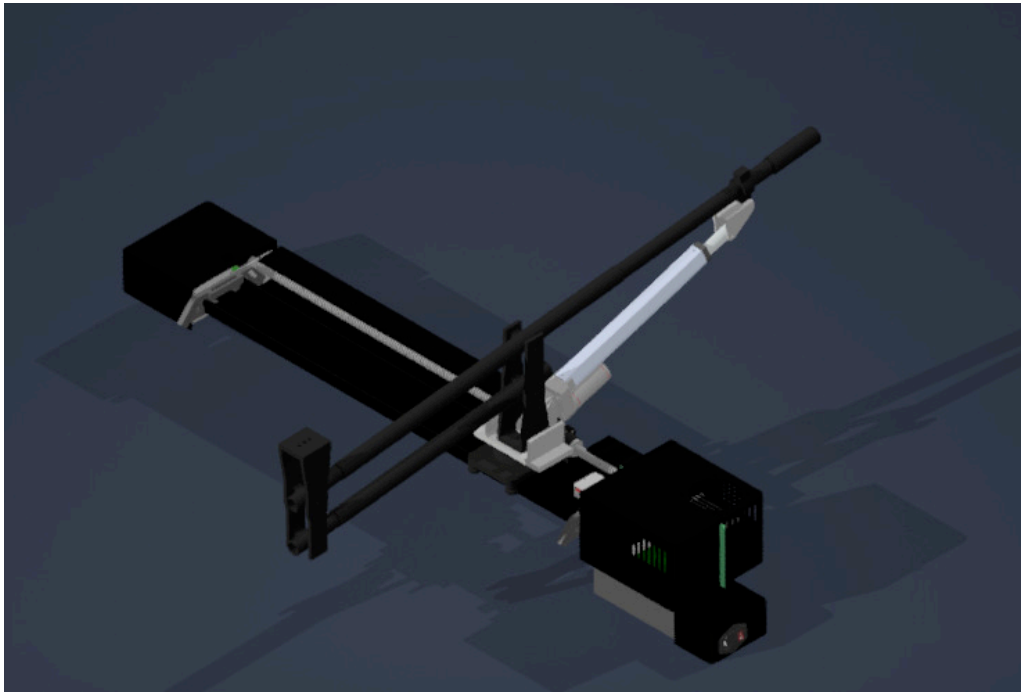


Fig. 2. Complete CAD assembly of the ENA system

Special parts were designed to complete four different purposes: contain the electronics, mount the NEMA 23 stepper motor, encapsulate the ball screw end bearings, and serve as the mechanical interface between the ball screw and carriage. Finite element analysis was performed for each of the main structural parts to find the minimal possible wall thickness and suitable material, see Section 2.3.3.

Material Selection. Using the results from FEA, the two main load-bearing structural components the motor mount bracket were fabricated using aluminium sheets, 3 mm thick. The CAD model for the two aluminium parts can be seen in Figures 3 and 4. The process of fabrication involved the bending of aluminium blanks into the two required parts without use of lap joints through bolts.

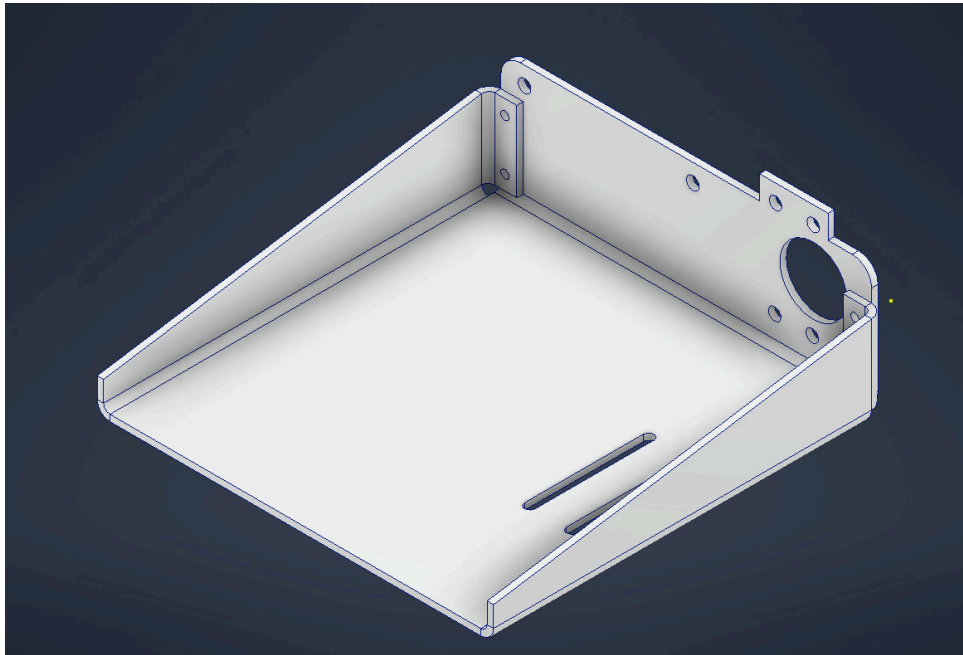


Fig. 3. CAD model of the main aluminium structural bracket .



Fig. 4. Detail view of the motor mounting face of the aluminium bracket.

The production of all secondary elements, such as cable management guides, sensor holders, was achieved by FDM-based additive manufacturing with PETG filament. The selection of PETG was justified by a good balance between fast prototyping time, sufficient tensile strength for light loads, and vibration resistance due to the slider movement.

Linear Transmission. The lateral translation mechanism consists of an SFU1204 ball screw with a 4 mm lead per revolution, supported at its fixed and floating boundaries by standardized BK10 and BF10 precision bearing blocks. Figure 5 shows the CAD detail of the ball screw carriage interface and bearing block assembly.

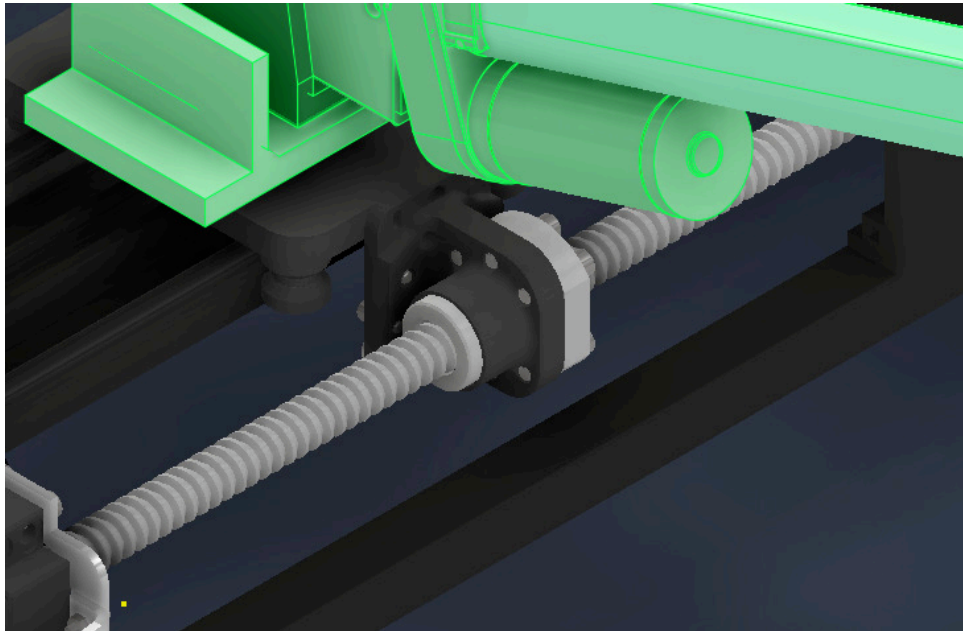


Fig. 5. CAD detail of the SFU1204 ball screw and carriage interface.

The selection of a ball screw over timing belt and ACME leadscrew alternatives was made following a comparative analysis of available literature and analogous projects, as formalised in Table 4. The ball screw was determined to offer superior structural rigidity, lower maintenance burden, eliminating the periodic re-tensioning required by toothed belts and greater suitability for field deployment conditions.

NEMA 23 stepper motor is connected to the ball screw by means of a flexible jaw coupling that allows for angular misalignment between the shafts as well as filters out high frequency harmonics emitted from the motor. See Figure 6, which shows the CAD model of the motor end with the mounting of the HC-020K encoder disk.

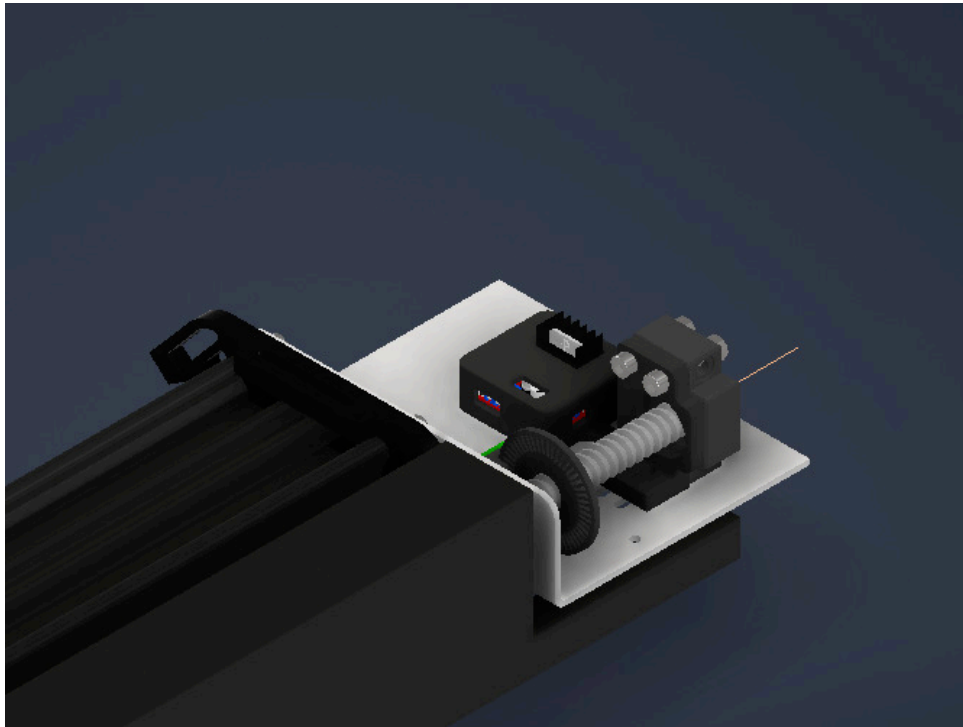


Fig. 6. CAD model of the motor end assembly.

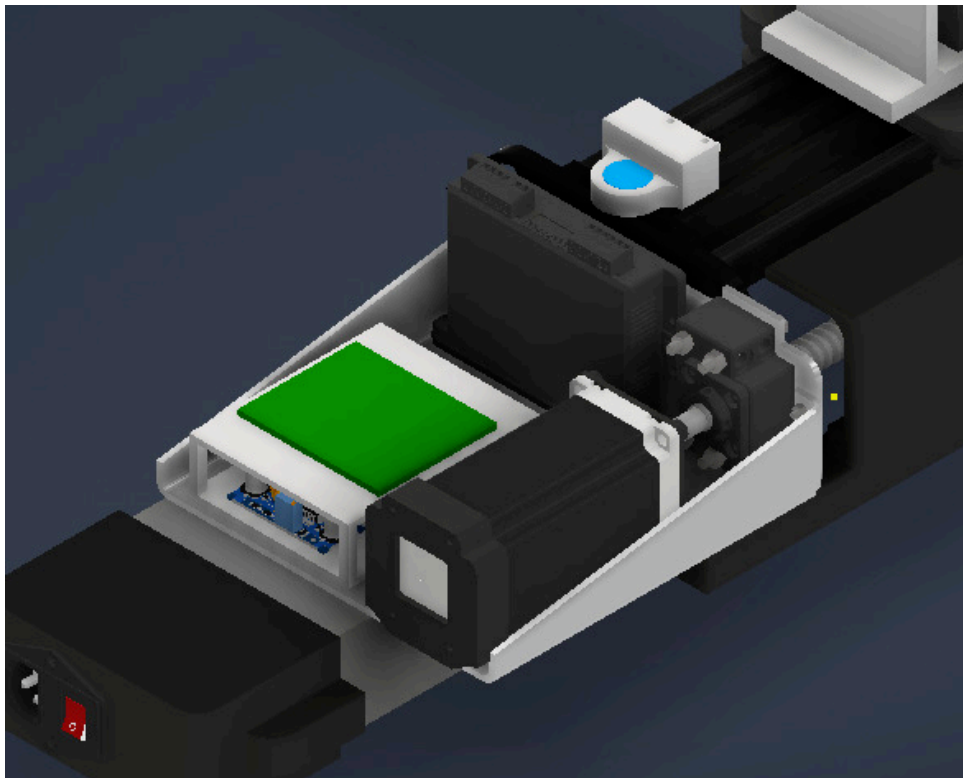


Fig. 7. CAD model of the carriage electronics.

The full assembly is mounted on a 70 cm linear slider frame, the prototype dimensions of 1.18 m (length) $\times$ 0.33 m (height) $\times$ 1.15 m (depth). Vertical translation along the Y-axis is

carried out using a combined jib-actuator system that is counterbalanced and directly attached to the moving cart. Structural joints which experience large bending loads are made from structural steel, while other load-free parts, such as cable carriers and sensors, are made of PETG to reduce dead weight. The total weight distribution of the working payload is shown in Table 5.

TABLE 5
Mass Distribution of the ENA System Payload

Component Description	Mass (kg)
Blackmagic 8K Cinema Camera Body	3.6
Professional Cinema Lenses	2.0
Accessory Support Cage and Rigging	1.2
Counterbalanced Camera Jib / Boom Assembly	10.0
Total Operational Payload	17.0
Design Baseline Capacity (Safety Margin)	20.0

Torque Analysis and Actuator Sizing

In order to confirm the proper function of the stepper motor NEMA 23 sizing, a dynamic torque analysis was performed based on the conservative design mass ($m = 20 \text{ kg}$), a smooth cinematographic acceleration curve ($a = 0.2 \text{ m/s}^2$) and the friction coefficient of precise linear slides ($\mu = 0.05$). The linear thrust force (F_t) necessary for overcoming the inertia and friction forces was calculated as follows:

$$F_t = (m \cdot a) + (\mu \cdot m \cdot g) \quad (2.1)$$

Substituting the operational parameters yields:

$$F_t = (20 \text{ kg} \cdot 0.2 \text{ m/s}^2) + (0.05 \cdot 20 \text{ kg} \cdot 9.81 \text{ m/s}^2) = 4.0 \text{ N} + 9.81 \text{ N} = 13.81 \text{ N}$$

The required rotational torque at the motor shaft (T_l) is derived as a function of the ball screw lead ($p = 0.004 \text{ m/rev}$) and the mechanical efficiency of the lead screw transmission ($\eta = 0.50$):

$$T_l = \frac{F_t \cdot p}{2\pi \cdot \eta} \quad (2.2)$$

$$T_l = \frac{13.81 \text{ N} \cdot 0.004 \text{ m}}{2\pi \cdot 0.50} \approx 0.01758 \text{ N} \cdot \text{m}$$

Incorporating an safety factor ($FS = 2$) to account for irregular lubrication or structural wear, the nominal design torque is established:

$$T_{\text{design}} = T_l \cdot FS = 0.01758 \text{ N} \cdot \text{m} \cdot 2 \approx 0.03516 \text{ N} \cdot \text{m}$$

Since the chosen NEMA 23 stepper motor has a holding torque of 1.2 to 3.0 N · m, the available torque is more than 30 times larger than the dynamic needs, and therefore the system operates without any step losses. The vertical motion is performed by a 1500 N DC linear actuator operated through an L298N H-bridge and the excess of force compared to the weight of the camera gear (166.8 N).

Structural Finite Element Analysis

The Finite Element Analysis (FEA) displacement analysis was performed for the most important structural bracket which holds the NEMA 23 stepper motor and slider electronics. This is the most mechanically important bracket of the system that carries a total static weight of around 1.7 kg, made up of motor body, DM542T driver, ESP32 controller, and the wiring harness attached to the lateral rail structure.

This simulation utilized the total gravitational force (16.67 N) acting on the mounting face of the motor and the rail interface faces being fixed geometrical constraints. The material for the structure chosen was the structural steel ($E = 200 \text{ GPa}$, $\nu = 0.30$). Figure 8 illustrates the contour of displacements.

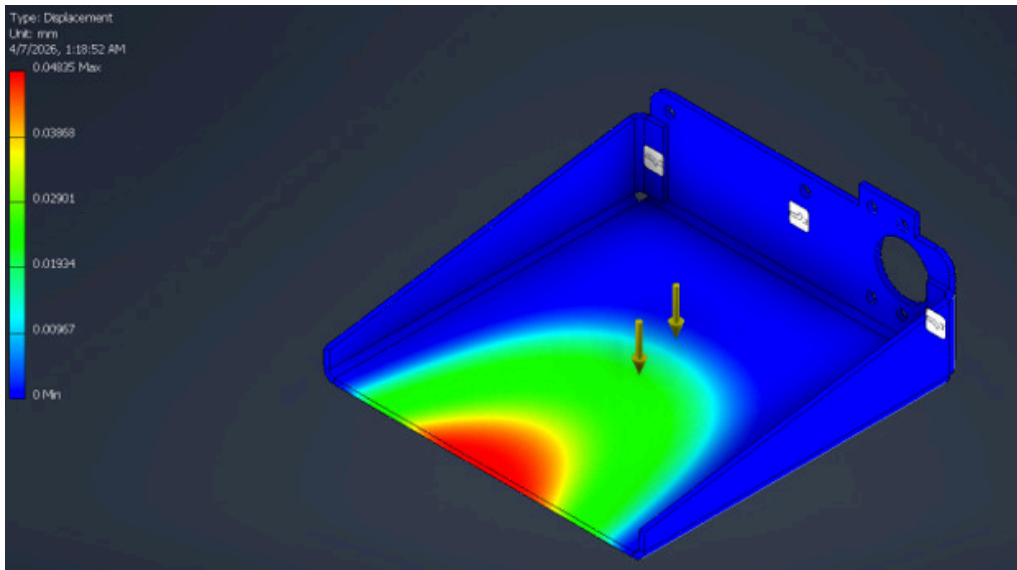


Fig. 8. FEA displacement contour map of the motor and electronics support bracket .

As can be seen from the figure 8, the largest total displacement for the structure when it is subjected to its design load does not surpass 0.04835 mm and this happens at the most distal point of the bracket geometry. Most of the surface of the bracket (which is shown in blue) has displacements that are close to zero, thus confirming the fact that the material operates in the elastic region of deformation.

The deformation of 0.04835 mm is structurally insignificant in its context. This amount of deformation is two orders of magnitude less than the linear resolution of the encoder of 0.04 mm/pulse and does not pose any threat to the possibility of inducing shaft misalignment of the motor with respect to the ball screw coupling. In this way, the simulation proves the validity of the chosen bracket configuration and materials.

Electronic and Control Architecture

The electronic system is partitioned into two independent assemblies: the **main control board**, mounted on the slider, and the **remote control unit**, carried by the operator. Both assemblies communicate exclusively via the ESP-NOW peer-to-peer wireless protocol integrated in the ESP32 microcontroller. Upon starting, both nodes immediately scan for their paired counterpart using pre-registered MAC addresses; connection status is reflected in real time on the remote control display before any motion command is accepted.

Main Control Board. The main board receives a single 24 V DC supply from the mains-connected regulated power supply. Voltage regulation is handled by two LM2596 step-down converters: one provides 12 V for the DC linear actuator, and a second provides 5 V for the

ESP32 receiver node and the HC-020K optical encoder. A 3.3 V–5 V logic-level converter interfaces the ESP32 output signals with the 5 V logic inputs of the DM542T stepper driver. The NEMA 23 stepper motor is driven directly from the 24 V rail via the DM542T driver. This power architecture is illustrated in Figure 1.

Main Power Supply Verification. The adequacy of the 24 V, 20 A mains power supply was verified against the maximum simultaneous current demand of all slider subsystems, as detailed in Table 6.

TABLE 6
Main Control Board Peak Current Demand

Subsystem	Peak Current (A)	Supply Rail (V)
NEMA 23 stepper motor	4.2	24
DM542T driver (logic)	0.1	24
DC linear actuator	2.0	12
L298N H-bridge	0.5	12
ESP32 receiver node	0.24	5
HC-020K encoder	0.05	5
LM2596 regulators (×2)	0.3	24
Total peak demand	7.39	—

The maximum current demand is of 7.39 A is equal to 37% of the total rated supply current of 20 A, resulting in a power reserve of 63%. This verifies the proper functioning of the chosen power supply within its rated specifications when operating at full load on both the axes.

Remote Control Unit. The remote control unit is an independent battery-powered embedded system featuring the following hardware:

- **ESP32 transmitter node:** runs HMI firmware and sends motion commands through ESP-NOW.
- **AS5600 magnetic encoder (dial input):** a 12-bit absolute magnetic rotary encoder which acts as a high-precision dial controlling of the X-axis. The user turns the encoder shaft and the resulting angle is converted into a target X-axis coordinate, so providing an accurate, jitter-free, mechanical wear-free positional input.
- **Analogue joystick:** provides Y-axis elevation with a proportional PWM signal sent to the L298N H-bridge.

- **TFT screen:** shows the current carriage position, connectivity state, operation mode.
- **Two push buttons:** To move through the HMI.
- **Power source:** a 3.7 V lithium-ion battery boosted to 5 V using a DC-to-DC converter.

The power consumption of all remote hardware was estimated based on measured static and peak currents and enough power was found to work during the filming session.

The key hardware parts, their model numbers and functions are summarized in Table 7.

TABLE 7
Electronic Component Specifications and System Roles

Component	Model	Key Specification	System Role
<i>Main Control Board</i>			
Stepper Motor	NEMA 23	Holding torque 1.2–3.0 N·m, 24 V	X-axis lateral drive
Stepper Driver	DM542T	4.2 A peak, 1/128 microstep, 5 V logic	Stepper power control and microstepping
DC Linear Actuator	COTS DC	1500 N force, adjustable stroke, 12 V	Y-axis elevation drive
H-Bridge Driver	L298N	2 A per channel, bidirectional, 12 V	PWM speed and direction for DC actuator
Optical Encoder	HC-020K	100 PPR (X2 quadrature), 5 V	X-axis closed-loop odometry
Microcontroller	ESP32	Dual-core 240 MHz, ESP-NOW, 5 V	Motion logic and wireless receiver
Voltage Regulator	LM2596 (×2)	24 V → 12 V and 5 V	Power regulation for all subsystems
Logic Converter	MOSFET module	3.3 V ↔ 5 V, bidirectional	ESP32–DM542T signal adaptation
<i>Remote Control Unit</i>			
Microcontroller	ESP32	Dual-core 240 MHz, ESP-NOW, 5 V	HMI firmware and wireless transmitter
Magnetic Encoder	AS5600	12-bit absolute, I ² C, 3.3 V	X-axis position dial input
Analogue Joystick	Generic	2-axis potentiometer, 3.3 V	Y-axis elevation control
TFT Display	ST7735	SPI, 128×160 px, 3.3 V	Position, status and mode display
Pushbuttons (×2)	Tactile	GPIO input, pull-up	A/B capture and mode selection
Battery	Li-ion 18650	3.7 V, capacity sized to session	Remote unit power source
Boost Converter	MT3608	3.7 V → 5 V, up to 2 A	Remote unit 5 V regulated supply

Remote Control Power Budget. The autonomy of the remote control unit power supply was evaluated based on the rated current consumption of all its parts at 5 V, as indicated in their datasheets presented in Table 8.

TABLE 8
Remote Control Unit Power Budget

Component	Typical Current (mA)	Operating Voltage (V)
ESP32 (average)	80	5.0
AS5600 magnetic encoder	6.5	3.3
ST7735 TFT display	20	3.3
Pushbuttons and misc	5	3.3
Boost converter losses ($\eta \approx 85\%$)	17	—
Total estimated draw	128.5	—

Loss in efficiency of boost converter was introduced using the following calculation: load current/efficiency of converter ($\eta = 0.85$). The estimated battery life t was determined using the formula:

$$t = \frac{C_{\text{bat}}}{I_{\text{total}}} = \frac{2200 \text{ mAh}}{128.5 \text{ mA}} \approx 17.1 \text{ h} \quad (2.3)$$

Autonomy of 17.1 hours is significantly more than the time of a regular filming session, proving that the chosen lithium-ion battery of 2200 mAh can offer enough autonomy without the need for charging between shooting days.

Remote Control Unit Enclosure Design

The mechanical design of the remote control enclosure was done side by side with the electrical one, since the physical limitations of the enclosure directly influenced the PCB design and placement of the components. Operational reliability in real field conditions was the main objective of the design: being handled constantly during the shooting sessions and moving all the time, all the internal components were fixed to certain positions on the PCB using machine screws, which prevented connector disconnect and displacement of the components due to vibrations or impact.

The enclosure itself was made of two interlocking pieces of PETG printed via FDM technology: front face and rear body, held together by corner screws. PETG was chosen for its resistance to impacts, dimensional stability in high temperatures of an outdoors filming environment, and ability to be quickly prototyped. Figure 9 shows the exterior CAD model of the enclosure.



Fig. 9. CAD render of the ENA remote control unit enclosure.

The operator interface has been designed specifically to be minimalistic with only those controls that are essential for cinematographic use being provided. Four user-input components have been provided on the front face of the interface. These are: the analogue joystick, used for controlling Y-axis elevation and also containing a push-button for confirmation of selections; a Menu button, which switches between display modes; a Set button, which navigates the current menu to switch between selections; and a power button, which switches off the device separately from the slider unit. The AS5600 magnetic encoder has been provided laterally as a dial on the right face of the enclosure, allowing X-axis positioning using the thumb/palm while keeping the front face uncluttered.

Figure 10 depicts the internal layout of the device, illustrating the arrangement of all the electronic components in the enclosure.

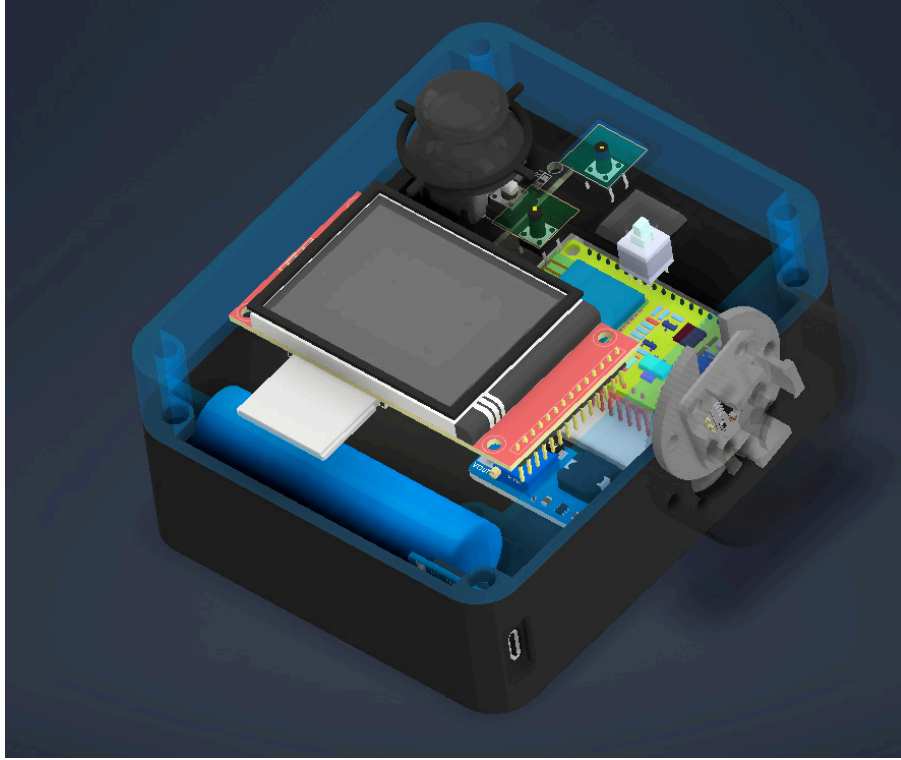


Fig. 10. Internal CAD layout of the remote control unit.

All components reside in their individual slots or posts, thus there is no movement at all between the parts when the system is operating. The TFT display is mounted flush and is held in place with four screws that go from the display bezel into the housing body. The ESP32 and the boost converters are secured to the internal floor using posts. The AS5600 encoder is pressed into the right lateral bore and held axially by the encoder knob retaining screw.

Optical Odometry Calibration

The implementation of the HC-020K optical encoder is one of the key sub-systems of the ENA control system design. Essentially, the role of the sensor in this case is to check whether movement occurs because moving the 17 kg object using an open loop stepper motor can be associated with a stall due to inertia or friction. The encoder allows us to transform the system from the open to the closed loop one, which will allow for monitoring of the camera carriage's linear position in millimeters by the ESP32 module.

The implementation process consisted of five iterative development steps, during which the odometry system was improved gradually to ensure stable position detection. These steps are listed in Table 9.

IR Transmittance of Disk Material. The first encoder disk was made out of 3 mm black PETG material. Even though black PETG is an opaque material to the naked eye, it allows for

TABLE 9
HC-020K Encoder Calibration Log — Challenges, Solutions, and Outcomes

Challenge	Engineering Solution	Outcome / Metric
IR transmittance of PETG disc	Carbonised matte black paint coating applied to all disk surfaces	Clean signal edges; complete IR beam blockage
Insufficient disk diameter (24 mm)	Redesigned disc: 55 mm diameter, 50 equidistant slots, ≈ 1.7 mm slot pitch	Reliable detection at all operational speeds
Need for higher resolution from 50-slot disc	X2 decoding: ISR triggers on both rising and falling edges	100 pulses/rev; 0.04 mm/pulse linear resolution
High-frequency noise (up to 213 pulses/rev)	ISR debounce: 5 ms protection window via <code>micros()</code> timer	Noise eliminated; stable 100 pulses/rev confirmed
Single-channel encoder; no direction data	DIR pin synchronisation with DM542T stepper driver signal	Full bidirectional odometry during panning and return traversals

a limited transmission of infrared light because of the HC-020K wavelength operation range. Solution: All the disks have been covered with a matte black paint, blocking the IR beam.

Mechanical Resolution. Insufficient circular clearance was present in the first disk with diameter of 24 mm for achieving the slot numbers that could match the width of the sensor beam. Solution: A new design of disk was done in which the diameter of the disk was increased to 55 mm with 50 evenly spaced slots.

X2 Quadrature Decoding. The ESP32 ISR was set to trigger on both signal transitions such that it effectively doubled the number of pulses to 100 pulses/revolution from the original 50 pulses/revolution. This was maintained as an advantage of design giving the linear resolution of 0.04 mm/pulse as given by Equation 2.4:

$$\Delta x = \frac{\text{Ball Screw Lead } (p)}{\text{Software Resolution}} = \frac{4.0 \text{ mm}}{100 \text{ pulses}} = 0.04 \text{ mm/pulse} \quad (2.4)$$

Software Debouncing. The initial tests gave false counts up to 213 pulses/rev caused by the mechanical micro-vibration and the irregularity at the edge of the disk. Solution: By implementing a temporal protection window of 5 ms in the ISR using `micros()`, only those interrupts that occur within the window of the previous one are ignored.

Bidirectional Odometry. The HC-020K encoder is a single channel encoder that gives no direction data intrinsically. Resolution: In the firmware, it was coded that for each encoder

interrupt, both the DIR pin of the DM542T driver and the encoder interrupts are read and the position accumulator is incremented or decremented accordingly.

Following calibration, the prototype transmits real-time linear position data in millimeters to a Python-based graphical monitoring interface, enabling trajectory verification without continuous manual intervention.

Human-Machine Interface Development

The design process of the ENA Human Machine Interface (HMI) was carried out using iterative prototyping technique. During the first phase of prototype creation, the basic functionalities of the system were validated using a graphical user interface developed using the Python language that communicated with the receiver node of the ESP32 board using the serial port. Using the developed interface, the system could perform real-time position tracking, manual direction control, and A/B trajectory sequence programming and execution. Figure 11 shows the Python based prototype interface.

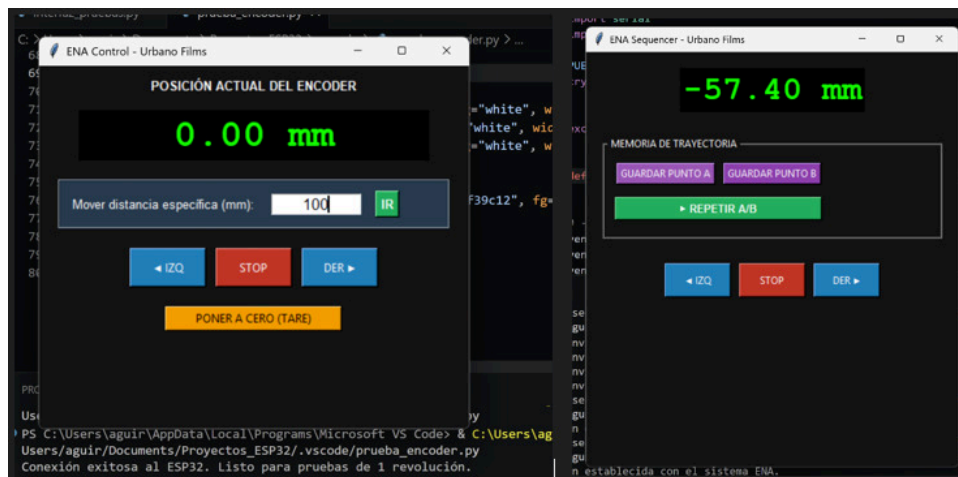


Fig. 11. ENA Sequencer Python graphical prototype interface.

These features have been verified in the Python prototyping stage and can be seen from Figure 11, which shows the primary functional features achieved: real-time read out of odometric positions, endpoints of trajectories, automated two-way A/B repetition, and manual control. The successful validation of these functions confirmed the optimal functioning of the firmware communication protocol and position-tracking algorithm before transitioning to the embedded remote control hardware.

The commissioning of the embedded remote control unit went through three rounds of iterations to arrive at the final configuration. Firstly, the analog joystick potentiometer for the Y-axis elevation had a center offset position of an ADC value of about 2975 instead of the

theoretical value of 2048. It thus led to the interpretation of the joystick idle state by the ESP32 microcontroller as an activation instruction for the linear actuator leading to ghost activations. This was addressed using asymmetric deadzone in the code for both sides of the center value with different lower and upper thresholds, resulting in no unintended actuator movements at all.

Secondly, the built-in tactile switch of the joystick was not working reliably and provided inconsistent readings when pressed. The tactile switch functionality was disabled and replaced with a separate physical pushbutton connected to GPIO 14 (BTN_SELECT) on the transmitter ESP32 board. Finally, button bounce on some physical switches was causing the microcontroller to read multiple edge transitions for every single button press leading to unwanted flickering of the user interface and activation of functions. This issue was addressed using rising edge triggered lock logic implemented in firmware, blocking all further button transition events in an interval starting with the first valid rising-edge event.

Currently, all joystick and button commands are programmed, calibrated and stable on the embedded remote control unit. There is ongoing work on the development of the TFT display subsystem which currently experiences some visual noise as a consequence of some kind of SPI bus interference artifact. An attempt to force-hardware-reset the display to flush out the video buffer content resulted in the panel staying in the blank white state (display unable to initialize). Resolution of this problem is the primary goal right now.

Firmware and User Interface Design

The firmware of the remote control unit was developed in C++ using the Arduino framework for the ESP32, structured around a finite state machine that manages five distinct display screens. The interface was prototyped using the Lopaka visual design tool for TFT-ESPI displays prior to firmware implementation, allowing the screen layouts to be validated before being translated into Adafruit_ILI9341 rendering calls. Figure 12 presents the main menu screen of the ENA remote control interface.



Fig. 12. ENA remote control main menu screen.

The interface is organised into four operational screens, each accessible from the main menu via the NAV button for tile selection and the joystick pushbutton (SW) for confirmation.

Manual Mode. Provides direct real-time operator control over both motion axes. Once activated via SW, the AS5600 magnetic encoder dial commands the X-axis carriage position proportionally: rotating the dial maps angular displacement to a target position in millimetres, which is transmitted as a destination command ('D') to the slider via ESP-NOW. The analogue joystick simultaneously controls the Y-axis DC linear actuator through upward ('U') and downward ('B') commands. The current carriage position is displayed in real time with a progress bar spanning the full 525 mm travel range. Control can be toggled on and off via SW without leaving the screen.

Homing. The slider sends the homing command ('H') and moves the NEMA 23 motor towards the limit switch at low speed until the limit switch is touched; thus, position zero is set. There is an animation on the screen while this process takes place. After the procedure finishes, the program goes back to the main menu automatically. The homing procedure is a requirement in firmware terms, and it must be done before using any other screens, such as the Manual Mode screen or A/B Sequence screen.

Sequence Mode of A/B Points. Permits setting up two points of trajectory (Point A and

Point B) through navigation of the carriage to these points by the encoder dial and confirmation of each point by pressing SW. Once both points have been defined, the automated sequence may be triggered, making the slider to perform repetitive motion between these two points. The number of cycles in sequence can be configured from 1 to 10 cycles, or be set to *infinite mode* (INF). Reset operation clears the stored points and stops the sequence, if performed.

Settings. Includes three system configuration parameters. Motor speed parameter defines the NEMA 23 travel velocity in percents of the maximum value (from 10 % to 100 %, with 10 % step incrementation). It is sent to the slider as velocity command ('V'). The motor test parameter commands the carriage to move to the geometrical center of the movement range (262.5 mm) for testing purposes. Axis lock parameter switches off X-axis encoder inputs, while Y-axis actuation remains active; it is convenient when vertical frame adjustment is needed for filming.

Chapter III

Results

System Integration

Prototype Assembly

The ENA prototype assembly is fully constructed according to the mechanical and electronic design criteria that have been discussed in Chapter 2. The integration process was carried out in a sequence: mechanical structure first, electronic connection second, and commissioning of firmware third. This was because each step could be checked for success before moving on to the next.

The aluminium mechanical brackets were formed out of 3 mm thick sheet metal and fixed to the linear frame rail that measured 70 cm long. The SFU1204 ball screw was fixed between the two bearing blocks (BK10 and BF10) and was connected to the NEMA 23 stepper motor through the flexible jaw coupling. The rolling carriages were fitted and tested to ensure that they could traverse the entire stroke distance of 525 mm without any interference. The jib boom and DC linear actuator were then fitted to the carriages. Figure 13 shows the ENA prototype assembled in the field deployment configuration.



Fig. 13. Assembled ENA prototype.

The main control board was wired and mounted within the brackets. The HC-020K optical encoder was installed on the rear shaft of the NEMA 23 motor via the custom 3D-printed

bracket. The remote control unit was assembled and paired to the receiver node via ESP-NOW using pre-registered MAC addresses. Wireless link establishment was confirmed on the TFT display of the remote unit prior to any motion test.

Outcomes of Integration

Integration of all subsystems, be they mechanical, electronic, or firmware ones, was successful in forming a prototype that functions properly. Homing sequence was confirmed to work correctly in guiding the carriage to the physical switch and defining position zero. A/B trajectories were programmed and performed consistently with mechanical behavior repeated over multiple attempts. Remote control was confirmed to reliably establish a wireless connection immediately after powering up the system.

Verification of Property

Performance of the ENA prototype was tested by four experimental tests aimed at evaluating positional repeatability, vibration behavior depending on the load, efficiency of operational setup, and trajectory consistency as compared with manual operation. Linear positions were measured with a Bosch GLM 30 laser distance meter from a fixed reference point.

Test 1 — Positional Repeatability

The positional repeatability of the X-axis closed-loop control system was evaluated by commanding the carriage to a fixed target position (Point A) across ten consecutive repetitions for each of three camera payload configurations. A single homing sequence was performed at the start of the test session; the carriage was then driven to Point A via the automated A/B sequence for each repetition. Table 10 presents the raw measurement data for all three configurations.

TABLE 10
Positional Repeatability Test — Raw Measurements (mm)

Rep.	Sony A6300	DJI Osmo Pocket 3	Blackmagic
1	315	313	314
2	313	314	317
3	314	313	315
4	316	313	314
5	313	314	314
6	313	314	315
7	312	314	316
8	314	314	314
9	314	315	313
10	315	313	313

The statistical parameters derived from Table 10 are summarised in Table 11.

TABLE 11
Positional Repeatability — Statistical Summary

Parameter	Sony	Osmo	Blackmagic
Mean position (mm)	313.9	313.7	314.5
Standard deviation (mm)	1.20	0.67	1.27
Maximum error (mm)	4.0	2.0	4.0
Payload mass (kg)	0.65	0.18	6.80

Figure 14 illustrates the positional measurements across all ten repetitions for each camera configuration, showing the distribution of measurements around the target position.

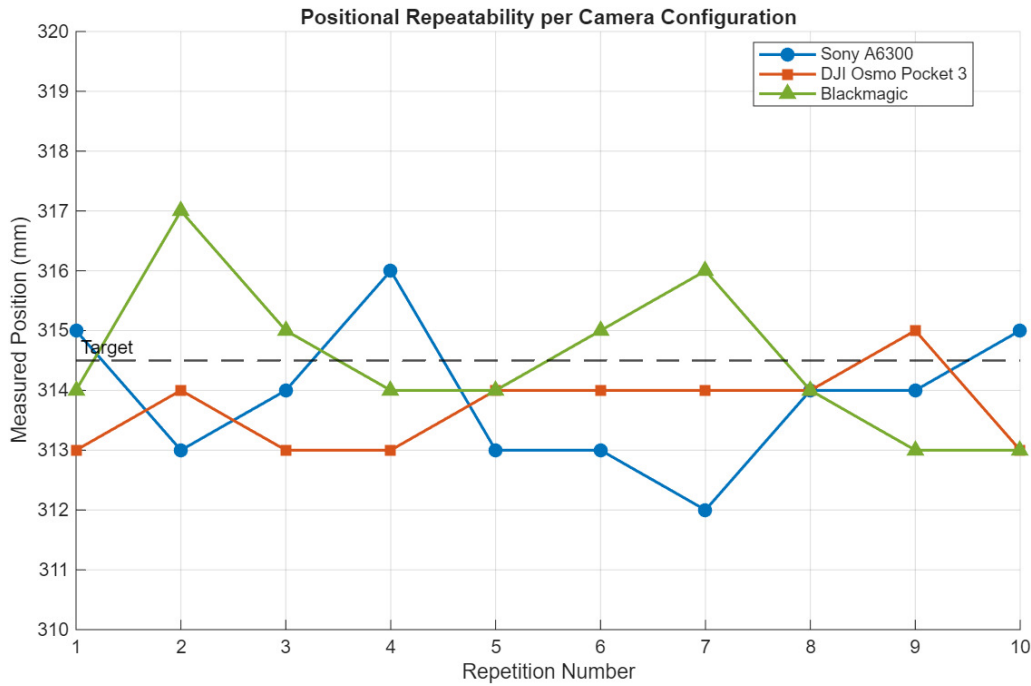


Fig. 14. Positional repeatability across 10 repetitions for three camera payload configurations.

Positional repeatability did not exceed ± 4 mm in any case, with the minimum value of the standard deviation being 0.67 mm for the lightest payload configuration (DJI Osmo Pocket 3). For the Blackmagic configuration, which is the heaviest one in our experiment (6.8 kg with the full boom) the standard deviation was 1.27 mm. It can be stated that the closed-loop control with encoders provides sufficient positional repeatability of the system under realistic production loads.

Test 2 — Load-Dependent Vibration Threshold

The maximum operational speed before the onset of visible image vibration was determined for each camera configuration by incrementally increasing the motor speed from 10 % to 100 % via the Settings menu of the remote control unit. Each level was evaluated visually through the camera viewfinder. The results are presented in Table 12.

TABLE 12
Load-Dependent Vibration Threshold per Camera Configuration

Speed (%)	Sony A6300	DJI Osmo Pocket 3	Blackmagic
10	No	No	No
20	No	No	No
30	No	No	No
40	No	No	No
50	No	No	Yes*
60	Yes*	No	Yes
70	Yes	No	Yes
80	Yes	Yes*	Yes
90	Yes	Yes	Yes
100	Yes	Yes	Yes

* Onset threshold speed.

Figure 15 summarises the maximum vibration-free operating speed for each configuration.

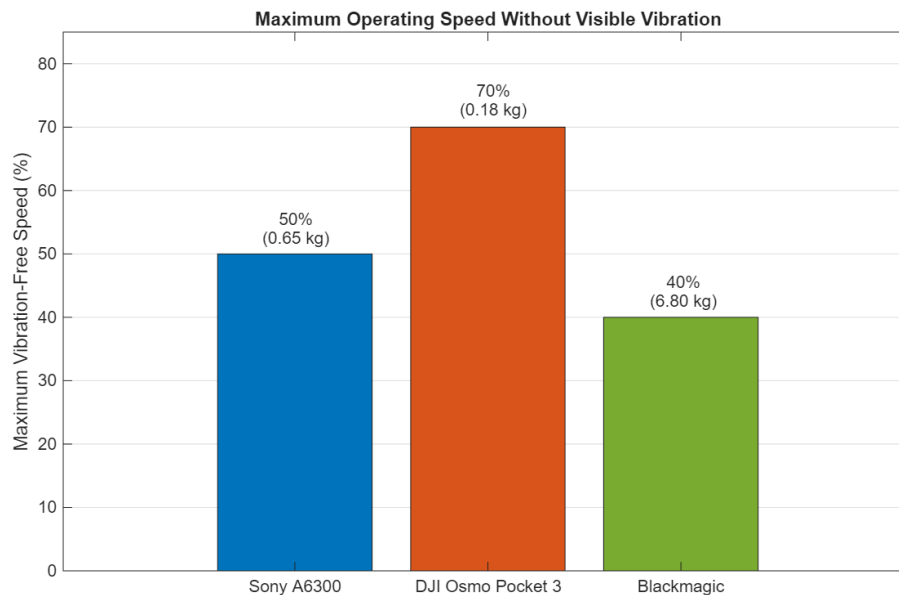


Fig. 15. Maximum vibration-free operating speed per camera configuration.

The results confirm an inverse relationship between payload mass and maximum vibration-free operating speed. No step loss was detected in any configuration across the full speed range, confirming that the NEMA 23 torque margin is sufficient for all tested payloads. These results establish recommended maximum operating speeds of 50 %, 70 %, and 40 % for the

Sony A6300, DJI Osmo Pocket 3, and Blackmagic configurations, respectively.

Test 3 — Operational Setup Time

The total deployment time from transportation state to ready-to-record state was measured for the Blackmagic configuration, representing the most demanding setup scenario. The results are presented in Table 13.

TABLE 13
Operational Setup Time Measurement

Phase	Time (min)
System assembly, camera mounting, power-on, homing and A/B definition	8
Requirement threshold	< 10
Margin	2 min (20 %)

The total setup time of 8 minutes satisfies the non-functional requirement of less than 10 minutes, with a 20 % margin.

Test 4 — Comparative Trajectory Consistency

The trajectory consistency of the ENA automated A/B sequence was compared against manual operator control across ten repetitions of the same commanded trajectory. The statistical comparison is presented in Table 14.

TABLE 14
Trajectory Consistency — ENA System vs. Manual Operator

Parameter	ENA System	Manual Operator
Mean position (mm)	314.5	324.5
Standard deviation (mm)	1.27	27.6
Maximum error (mm)	4.0	100.0
Step loss detected	No	N/A
Physical effort required	No	Yes
Operator fatigue	None	Reported

Figure 16 illustrates the positional measurements of both methods across the ten repetitions.

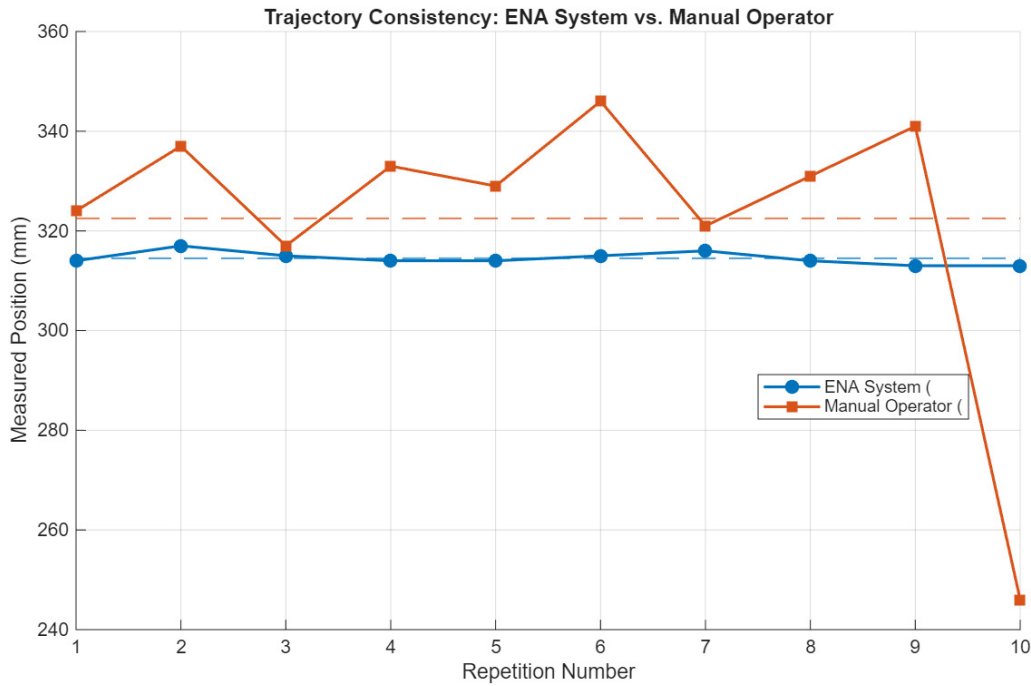


Fig. 16. Trajectory consistency comparison between the ENA system and manual operator.

The ENA system achieved a 21.7-fold reduction in positional standard deviation relative to manual control (1.27 mm vs. 27.6 mm), with a maximum error 25 times smaller (4 mm vs. 100 mm). Qualitative feedback from the camera operator confirmed that use of the ENA system produced significantly less physical fatigue compared to equivalent manual trajectories.

Discussion

It is clear from the test findings that the ENA technology fulfills its primary design requirements under typical production conditions, although a single hardware constraint imposed by manufacturing variability has been identified.

Positional Repeatability. The closed loop encoder feedback system has managed to maintain positional consistency in all the load setups by ensuring that there are standard deviations that remain within the range of 1.30 mm. The significance of the comparison test to manual handling lies in the fact that the ENA system has managed to produce an improvement in positional standard deviation, which cannot be replicated manually.

Load-Dependent Vibration. The onset of visible image vibration at moderate speed levels was an unexpected finding. Post-test mechanical inspection identified the root cause as a slight geometric curvature in the SFU1204 ball screw shaft, likely introduced during manufacturing or shipping, which generates a periodic radial excitation force amplified at higher rotational speeds and heavier loads. The conclusion obtained above does not mean that the

choice of the ball screw transmission is incorrect, since the system should have high rigidity and small backlash. Nonetheless, the conclusion is made that the straight geometry of the new screw would prevent vibration and increase speed limit.

Operational Efficiency. The total time of deployment amounting to 8 minutes meets the required 10-minute time with a 20 % buffer. In combination with the reported decrease in physical exhaustion, it proves that the objective of the ergonomics of the system is to decrease the effort required to execute precise motions and not to automate the operator of the camera.

System Limitations. The primary operational limitation identified during validation concerns maximum operating speed under load. Due to the geometric curvature of the ball screw shaft, cinematographic shots requiring fast lateral camera movements are not achievable without visible image vibration in the current prototype. Specifically, the recommended maximum vibration-free operating speeds are 70 % for lightweight configurations, 50 % for medium payloads, and 40 % for the heaviest tested configuration. This constrains the system to slow and medium-speed tracking shots, which represent the majority of professional cinematographic applications but excludes high-speed action sequences. Replacement of the ball screw with a geometrically straight component of equivalent specification is identified as the primary corrective action to extend the operational speed range in the next development iteration.

Chapter IV

Conclusion

The conception, implementation, and experimental validation of the ENA (Enfoque y Navegación Automatizado) robotic camera system were successfully accomplished, fulfilling all the five specific goals set up for this project.

The mechanical frame was manufactured to accommodate 20 kg of payload by means of a ball screw drive and a balanced jib-actuator mechanism. FEA analysis showed the appropriateness of the mechanical design, with maximum displacement of the bracket not exceeding 0.04835 mm under working load.

The control system based on two ESP32 units, stepper and H-bridge driver, and optical encoder was developed. ESP-NOW wireless communication was realized, and the closed loop odometric system provided a proved resolution of 0.04 mm/pulse. All programmed movements, including lateral, cranes-like elevating, and automatic A/B motion sequences were implemented and validated.

The autonomous motion sequence provided the origin reference at the beginning of each run. The man-machine interface allows configuring and executing any programable trajectory in the measured setup time of 8 minutes which is 20 % the 10 minute requirement limit.

Experimental results demonstrated the higher consistency of the system compared to a manual operation. The positional standard deviation of the camera was 1.27 mm versus 27.6 mm for manual operation. It means that in each shot the camera will be placed in virtually the same spot without any physical effort.

Recommendations

Based on the findings of the design, implementation, and validation phases, the following recommendations are proposed for future development iterations of the ENA platform.

Third-Axis Integration. A rotary pan axis at the camera mount would extend the system from two to three degrees of freedom, enabling full pan-tilt-track cinematographic sequences. This would significantly expand the shot repertoire available to production companies and increase the competitive positioning of the platform relative to commercial systems.

PCB Design. The current prototype relies on development boards and point-to-point wiring. The design of a custom printed circuit board integrating the ESP32, voltage regulators, logic level converter, and motor driver interfaces would improve reliability, reduce wiring complexity, eliminate potential connector failures under field conditions, and reduce the overall footprint of the electronics assembly.

Battery-Powered Operation. The current slider system requires a mains AC power supply, limiting deployment to locations with electrical infrastructure. The integration of a high-capacity lithium battery pack with voltage regulation for the 24 V, 12 V, and 5 V rails would enable fully portable operation across outdoor and remote filming locations.

Quantitative Speed Characterisation. Future validation should include a quantitative measurement of the actual carriage velocity in mm/s corresponding to each speed percentage setting, allowing production teams to specify and reproduce exact movement velocities rather than relative percentage values.

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