

Design and Construction of an Automation System for Battery Drop Test Machine

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Abstract

This research presents the design and construction of an automated battery drop test machine developed to overcome the high costs of commercial equipment and the physical limitations of existing testers regarding large-scale battery research. The proposed system features an adjustable drop height ranging from 300 mm to 1500 mm and utilizes a stainless-steel hinge clamping mechanism for secure battery positioning. The control architecture is built upon a Siemens LOGO!8 PLC integrated with an HMI touchscreen, employing Finite State Machine (FSM) principles to ensure precise operation in both manual and automatic modes. To prioritize user safety, the machine is housed within a secure test chamber equipped with a CO₂ fire suppression system and water cooling to mitigate thermal runaway risks.

Experimental validation was conducted following the testing protocols outlined in the IEC 62133 and MIL-STD-810H standards, utilizing battery samples weighing up to 80 kg. Results confirmed the machine's ability to accurately release batteries in various orientations, including 6 surfaces, 12 edges, and 8 corners, with impacts consistently aligning with target positions. The system offers a flexible, cost-effective, and safe alternative for the continuous testing of diverse battery types, particularly those intended for electric vehicles and energy storage systems. Future work will focus on expanding compliance to include UN 38.3 and UL 2054 standards for international product certification.

Keywords: Automated test machine, Battery drop test, Lithium-ion batteries, PLC control system, Product design

INTRODUCTION

Currently, battery production is crucial for global technological and economic development. This is because batteries are the primary energy storage for electronic devices like smartphones and laptops, as well as increasingly popular Electric Vehicles (EVs) and Renewable Energy Storage systems [1], [2], [3]. The demand for clean energy and reduced greenhouse gas emissions emphasizes the importance of battery research and development, especially for Lithium-ion (Li-ion) batteries, focusing on performance, safety, lifespan, and production costs [2].

Furthermore, battery production plays a significant role in the energy transition from fossil fuels to renewable energy sources, which have high production uncertainties. Effective energy storage systems enhance grid stability and support the expansion of renewable energy [3], [4]. Therefore, research and development in battery production innovation are essential for global energy security and environmental sustainability.

The drop test is a vital method for evaluating the safety and reliability of batteries, particularly Li-ion batteries widely used in electronics, EVs, and portable devices [5], [6]. This test simulates drops or impacts that may occur in daily life to assess the battery's structural integrity, as well as to prevent short circuits, electrolyte leakage, or even fire and explosion [6], [7].

Battery safety standards prioritize the drop test to define testing conditions that ensure batteries remain safe after severe impacts [7], [8]. Key standards include IEC 62133 (international safety requirements for portable lithium-ion batteries), UN 38.3 (certification required for the safe global transportation of lithium batteries), and UL 2054 (a standard assessing the safety of household and commercial batteries against fire and explosion risks). These test results provide critical information for product certification and build consumer confidence. A lack of proper drop testing can lead to safety risks to life, property, and the environment [7], [8]. Research shows that drop testing can reveal weaknesses in enclosure design, internal protection systems, and cell arrangement within the battery. This information helps developers improve designs to enhance battery safety and lifespan effectively [5], [7]. This highlights the significant importance of battery drop testing in battery development.

Currently, there are battery drop test machines available, such as figure 1 Amade-Tech IEC 62133 Battery Drop Tester (Amade-Tech, China) and DGBell BE-8108 (EMIN, Vietnam). Both are expensive and have fixed structures that cannot accommodate large batteries, which are necessary for certain types of development and research, such as tank batteries encased in large frames as illustrated in figure 2.



Figure 1: Amade-Tech Battery Impact Discharge Tester



Figure 2: Example of a battery for a tank

This research thus proposes the design and construction of a battery drop test machine for initial drop test data collection for research purposes. This machine can drop batteries from various positions to test multiple drop configurations, using affordable, basic equipment and incorporating automated safety features.

A battery drop test machine is essential for evaluating battery safety, especially for Li-ion batteries. These batteries must meet international standards, such as IEC 62133-2:2017 [8], [9], to ensure they can withstand impacts from dropping without becoming hazardous. Key features of such machines typically include:

Adjustable Drop Height: The machine allows for drop heights ranging from 300 mm to 1500 mm, simulating various drop scenarios (Guangdong Bell Experiment Equipment, China).

Pneumatic Gripping System: A pneumatic system secures the battery in place before release, ensuring precise and safe testing (Guangdong Bell Experiment Equipment, China).

Safe Test Chamber Structure: The test chamber is often constructed from high-quality stainless steel, featuring a safety glass door and an explosion-proof system for user protection [10].

PLC and Touchscreen Control: Users can configure test parameters and operate the machine via a touchscreen connected to a PLC system, which makes operation convenient and accurate (Guangdong Bell Experiment Equipment, China).

International Standard Compliance: Test machines are designed to comply with standards like IEC 62133, UL 2054, and UN 38.3. This ensures that batteries passing the tests are safe for use and transport [11].

The researchers will incorporate all these features into the design, except for the official equipment certification for IEC 62133, UL 2054, and UN 38.3 standards. Evaluating the machine for full compliance requires further testing, which is beyond the scope of the current research.

METHODS

The methodology follows Norton [12] for its systematic integration of design theory and practice. This approach ensures that critical safety and structural calculations are verified prior to construction, enabling precise refinements for testing heavy-duty batteries as illustrated in figure 3.

1. Specification Analysis

This involves identifying user requirements, including adjustable height, a pneumatic gripping system, a PLC system structure, a safe test chamber structure, the range of battery sizes to be tested, and the maximum supported battery weight.

2. Information Gathering & Conceptual Design

This step focuses on studying technical information related to pneumatic systems, PLCs, and touchscreen connectivity. It also involves researching impact-resistant and explosion-proof materials such as stainless steel and tempered glass. Additionally, existing battery drop test machines on the market are surveyed for comparative analysis.

3. Preliminary Design & Calculation

This stage includes calculating the impact force generated by batteries when dropped from various heights. The structural components are sized to withstand impact forces without deformation. Suitable materials are selected, including stainless steel 304 for the main structure, tempered glass for the test chamber door, and pneumatic cylinders for the gripping system.

4. Detailed Design

This stage involves creating 2D/3D drawings using CAD software. The drawings will illustrate the following details: the clamping mechanism, the lifting and dropping system, the touchscreen control panel, and safety systems (e.g., safety switches, door sensors).

5. Prototype & Testing

A prototype will be constructed to test the actual operation. This test will involve dropping batteries at specific positions as shown in figure 4, which include C: Corner, E: Edge, and S: Surface. The objective is to verify if the automated battery drop test machine can accurately drop batteries at the desired locations, ensure operational safety, and confirm compliance with relevant standards. Any identified issues will lead to design revisions.

6. Finalization

The design will be refined based on the test results. Subsequently, an operation and maintenance manual will be prepared.

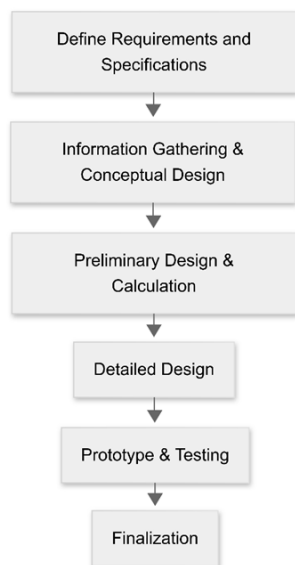


Figure 3: The development process for the automated battery drop test machine

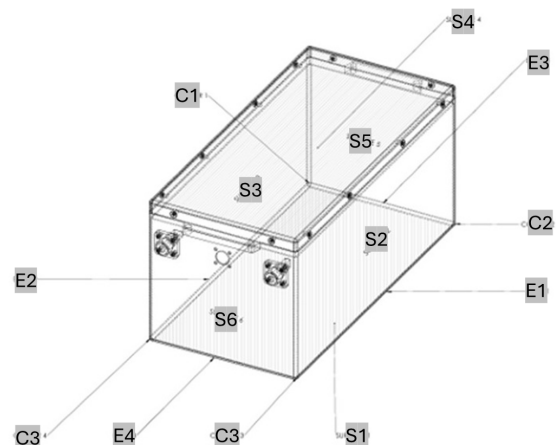


Figure 4: Battery drop location

RESULTS AND DISCUSSION

1. Result of Requirements and Specifications

The automated battery drop test machine features an adjustable drop height of 300–1500 mm. Batteries are secured by a bracket attached to stainless steel hinges, allowing them to drop onto a base below. The control system for the battery drop test machine and safety devices utilizes a PLC controlled by an HMI. The test chamber is constructed within a stainless-steel container and accommodates batteries up to 480 mm long (excluding handles and terminals), 235 mm wide, and 230 mm high, with a maximum weight capacity of 100 kg.

2. Result of Information Gathering and Conceptual Design

For the PLC control system, the Siemens LOGO!8 version 8.4 [13] was selected due to its industrial capabilities [14], [15], [16], [17] and cost-effectiveness compared to other brands in the same class. It allows for sufficient I/O expansion to meet requirements. The HMI chosen is the Samkoon SK-070QS-G, a touchscreen model with an Ethernet port for communication with the LOGO!8 via Modbus TCP [17], which is an industry standard. The structure of the automated battery drop test machine and safety systems, such as glass, fans, and lighting, are made from impact-resistant and explosion-proof materials.

Damaged batteries that may ignite or explode are managed by CO₂ suppression [18], [19], [20]. CO₂ is a non-flammable gas that can reduce oxygen in the affected area, thereby extinguishing flames. Large quantities of water are also used to reduce heat [21], [22], [23] from thermal runaway [24], preventing adjacent cells from being affected. Once the situation is stable, CO₂ is extracted by an exhaust fan, allowing safe access to retrieve the battery.

3. Result of Preliminary Design and Calculation

The size and power hoist for lifting the heaviest battery (100 kg), with a hoist radius of 20 cm were calculated using the torque equation, where W is the weight (in newton, N) representing the force exerted on an object due to gravity, m is the mass (in kilogram, kg) indicating the amount of matter in an object (In this case 100 kg), g is the acceleration due to gravity (in meter per second squared, m/s^2) which is a constant value, approximately $9.81 m/s^2$ on Earth, τ is the torque (in newton-meter, Nm) representing a rotational force, F is the force (in newton, N) applied to create the torque (in this case, the weight, W , of the battery, which is 981 N), and r is the radius (in meter, m) of pulley hoist which lifts the battery, which is 0.2 m in this case.

$$W = m \times g \quad (1)$$

$$W = 100 \text{ kg} \times 9.81 \text{ m/s}^2 = 981 \text{ N}$$

$$\tau = F \times r \quad (2)$$

$$\tau = 981 \text{ N} \times 0.2 \text{ m} = 196.2 \text{ Nm}$$

Therefore, the motor driving the hoist must have a power greater than 196.2 Nm.

The impact force was calculated to determine the material for the drop base, with a maximum specified height (h) of 1.5 m. The calculation used the following equation, where PE is potential Energy (in joule, J) representing

the energy an object possesses due to its position or state, h is the height (in meter, m) which is the vertical distance from a reference point (1.5 m in this case).

$$PE = m \times g \times h \quad (3)$$

$$PE = 100 \text{ kg} \times 9.81 \text{ m/s}^2 \times 1.5 \text{ m} = 1471.5 \text{ J}$$

Assuming no air resistance, the potential energy (PE: 1,471.5 J) is entirely converted into kinetic energy (KE) upon impact with the ground, where KE is the kinetic energy (in joule, J) representing the energy an object possesses due to its motion, and v is the velocity (in meter per second, m/s) indicating the speed of the object in a given direction.

$$PE = KE \quad (4)$$

$$KE = \frac{1}{2} \times m \times v^2 \quad (5)$$

$$1471.5 \text{ J} = \frac{1}{2} \times 100 \text{ kg} \times v^2$$

$$v = 5.42 \text{ m/s}$$

From (5), the obtained velocity is 5.42 m/s. Thus, the impact force depends on the stopping time or distance of the object (Δt or Δx). If the surface is hard, the stopping distance is short, and the force will be high. If the surface is soft, the stopping distance is long, and the force will be lower. Assuming the object stops within a distance of 2 cm (0.02 m), the Work-Energy theorem is applied, where d is the stopping Distance (in meter, m) representing the distance over which the object decelerates to a stop.

$$F \times d = \frac{1}{2} m \times v^2 \quad (6)$$

$$F \times 0.02 \text{ m} = 1471.5 \text{ J}$$

$$F = 73,575 \text{ N}$$

Thus, the impact force is 73,575 N. Suitable materials for the impact base include reinforced concrete or steel [25]. Therefore, these materials are used as a base to support the battery from being dropped.

The pneumatic system operates at a pressure of 5 bar, in accordance with industrial standards [26], to control the safety valves for water and CO₂.

Regarding control logic, the PLC control system [27] that operates the battery drop test machine and its safety system employs the finite state machine (FSM) principle [28]. FSM is a method used in designing sequential logic by considering changes in system states based on received inputs, commonly applied in industrial automation. This approach breaks down potential scenarios, defining when each scenario occurs and which devices are active during that scenario.

4. Result of Detailed Design

The automated battery drop test machine was designed using CAD software, as shown in figure 5. The test chamber's layout, including a rough sketch of its internal components, is presented in figure 6. Please note that these designs may undergo future modifications.

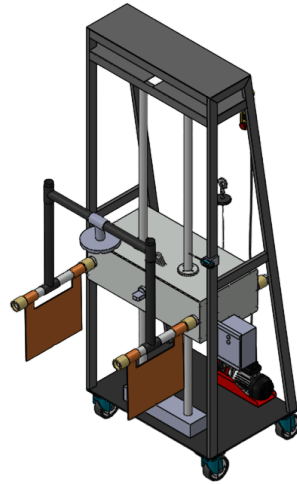


Figure 5: Automated battery drop test machine simulation model on CAD software

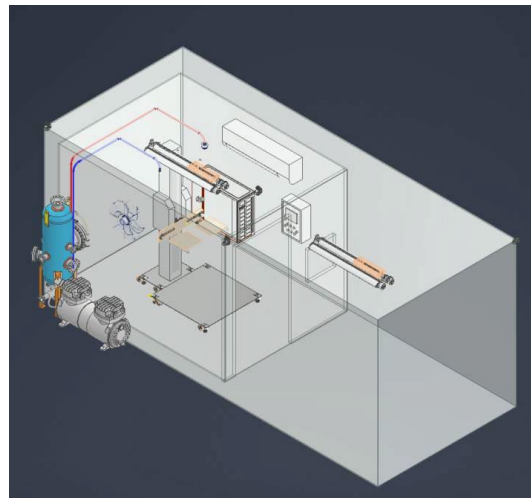
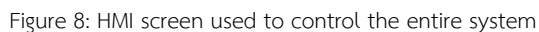


Figure 6: Test chamber diagram including safety devices

The control program, written according to the FSM design and utilizing Function Block Diagram (FBD) language, is presented in figure 7. FBD conforms to the IEC 61131-3 standard [29], [30] for industrial automation programming, allowing for language conversion. The automatic battery drop test system includes both manual and automatic control modes. Manual control is operated via the HMI touchscreen for individual devices, while automatic control is activated by a battery temperature sensor based on predefined conditions, as shown in figure 8.



A prototype chamber was developed within a container measuring 2.5 x 6 x 2.6 meters, as shown in figure 9. For safety, Circuit Breakers independently control the power to each system.



Figure 9: External of test chamber

The interior is divided into a control and observation room, depicted in figure 10, and a testing room, shown in figure 11. The control cabinet will be relocated to the testing room, and observations will be made through safety glass. The automated battery drop test machine will be positioned in the testing area. An impact absorption base and integrated safety systems, as designed, will be present. Figure 11 illustrates the setup for testing all mechanisms and safety systems to ensure they function as designed.



Figure 10: Control and observation room



Figure 11: Impact battery test chamber

The system underwent actual testing to gather data for improvement. Drop tests were conducted according to IEC 62133 standards from a height of 1.0 m onto a concrete surface, and MIL-STD-810H [31] standards to assess environmental durability from a height of 1.22 m onto a concrete surface. Both tests involved dropping the battery in 6 different orientations (sides), 12 edges, and 8 corners.

Table 1: Result of battery drop via the proposed automated battery drop test machine

Sample No.	Orientation of testing	Number of tests (Times)	OCV before test (Vdc)	OCV after test (Vdc)	Battery Result	Target Position
1	S1	1	26.69	26.69	NF,NE	Yes
1	S2	1	26.69	26.69	NF,NE	Yes
1	S3	1	26.69	26.69	NF,NE	Yes
1	S4	1	26.69	26.69	NF,NE	Yes
1	S5	1	26.69	26.69	NE,NF	Yes
2	S1	2	26.38	26.38	NF,NE	Yes
2	S2	2	26.38	26.38	NF,NE	Yes
2	S3	1	26.37	26.37	NF,NE	Yes
2	S4	1	26.37	26.36	NF,NE	Yes
2	S5	1	26.36	26.36	NF,NE	Yes
2	E1	2	26.36	26.36	NE,NF	Yes
2	E2	2	26.36	26.36	NF,NE	Yes
2	E3	2	26.36	26.36	NF,NE	Yes
2	E4	2	26.36	26.36	NF,NE	Yes
3	S6	2	26.30	26.30	NF,NE	Yes
3	C1	1	26.30	26.30	NE,NE	Yes
3	C2	1	26.30	26.30	NF,NE	Yes
3	C3	1	26.30	26.30	NF,NE	Yes
3	C4	1	26.30	26.30	NF,NE	Yes

Note: The data presented in this table are partial results, representing a specific subset of the ongoing sequential testing process.

The battery being tested had a length of 480 mm (excluding handles and terminals), a width of 235 mm, a height of 230 mm, and weighed 80 kg. It was secured in various positions as illustrated in figure 4. An example of a test position is S5, shown in figure 12. After each drop, the battery was observed for 20 minutes before proceeding to the battery testing section. The results obtained from using the designed automated battery drop test machine are as follows in table 1, where Sample No. refers to the battery used in the automated battery drop test machine, Orientation of testing specifies the part of the battery subjected to the impact comprising S (surface), E (edge), and C (corner), Number of tests indicates the quantity of tests performed, OCV before test represents the open-circuit voltage of the battery prior to the impact, OCV after test represents the open-circuit voltage of the battery subsequent to the impact, Battery Result describes the condition of the battery following the impact (where NF or No Fire signifies the absence of ignition, and NE or No Explosion signifies the absence of an explosion), and Target Position indicates whether the battery impacted the intended point, verified through video analysis.



Figure 12: Battery drop test in case of S5 position

The automated battery drop test machine was observed to accurately position and release batteries from the specified heights for all test locations. The integrated automatic safety monitoring system enabled continuous experimentation. Each test required a minimum 20-minute observation period, but operators were not required to be present throughout this time.

Preliminary results indicate a high level of safety for batteries subjected to this drop test, as no ignition or explosion occurred. Furthermore, the potential difference (voltage) of most batteries remained at normal levels after testing. The constant OCV confirms that the internal structure of the battery cells, such as the electrodes and separator, did not suffer physical damage from the impact. This indicates that the battery's manufacturing standards are robust enough, allowing the external casing to provide adequate shock absorption to protect the internal electrochemical components.

CONCLUSION

This research focuses on the design and development of the automated battery drop test machine for battery research and development. The key objectives were to utilize inexpensive, fundamental components and to accommodate large-sized batteries, which addresses a limitation found in current commercial testing equipment.

The developed test machine successfully meets all specified requirements. These include an adjustable drop height ranging from 300 mm to 1,500 mm, a battery clamping system featuring a stainless-steel hinge mechanism, an automatic control system integrated with a Siemens LOGO!8 PLC and an HMI touchscreen, and a secure test chamber housed within a container with a CO₂ gas fire suppression system.

Testing conducted by simulating the conditions specified in the IEC 62133 and MIL-STD-810H standards demonstrated the machine's accurate and efficient performance. It can test batteries in various orientations (6



faces, 12 edges, 8 corners) and supports battery weights up to 80 kg. The drop impacts consistently align with the intended positions.

The developed system offers several advantages: operational flexibility, as it can accommodate a wide range of battery sizes, including large batteries for tanks; cost-effectiveness, due to its use of inexpensive basic components compared to commercial machines; high safety, with an automated safety system that minimizes risks to operators; and continuous operation, as its automation enables continuous testing without constant supervision. To emphasize the practical advantages of the proposed system, a comparison between the developed prototype and existing commercial equipment is provided. While commercial testers, such as those from Amade-Tech and DGBell, offer standardized testing environments, they often possess rigid structures that cannot accommodate large-scale batteries and are limited by low weight capacities. In contrast, the proposed machine provides a flexible and cost-effective solution specifically designed for large-frame batteries with a weight capacity of up to 100 kg. The detailed comparison is summarized in Table 2:

Table 2: Comparison of features between commercial testers and the proposed automated machine

Features	Commercial Testers (Amade-Tech, DGBell)	Proposed Automated Machine
Structural Design	Fixed and rigid; limited battery size	Flexible; accommodates large-scale frames
Max Battery Weight	Limited (e.g., 5 kg for BE-8108 model)	Up to 100 kg (Validated at 80 kg)
Drop Height Range	300 – 1500 mm	300 – 1500 mm
Control Interface	Proprietary manufacturer software	Industrial PLC (Siemens LOGO!8) + HMI
Safety Systems	Standard test chamber	Enhanced CO2 suppression and water cooling
Cost-Effectiveness	High acquisition cost	Low cost (utilizes basic components)

For future development, the test machine can be applied to the research and development of various batteries, particularly large batteries used in electric vehicles and energy storage systems. Future enhancements may include expanding its capability to support additional international standards, such as UN 38.3 and UL 2054, for product certification. This research demonstrates that developing testing equipment with an appropriate approach can create effective and cost-efficient alternatives for battery technology research and development in Thailand.

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During the preparation of this manuscript, AI-based tools were employed to assist with grammar and language refinement. Specifically, grammar checking and stylistic suggestions were provided by an AI language model to enhance clarity and readability. All content was subsequently reviewed and edited by the authors to ensure accuracy and appropriateness.

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