Force-feedback Cable-driven Leveling System for Modular Construction Installation

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Abstract -

Modular construction (MC) has gained increasing adoption due to its advantages in productivity, standardization, and off-site fabrication. However, the on-site installation of MC modules remains labor-intensive and highly dependent on repetitive manual leveling using a hand chain. This manual process introduces operational risks and prolongs installation time. To address these limitations, this study presents a force-feedback cable-driven leveling system (FCLS) for MC installation. The system employs four winch units to adjust cable lengths at the corners of the lifting frame, enabling roll-pitch pose control without requiring workers to perform iterative adjustments at height. A force-based perception model is developed to estimate the center of gravity (CoG) in real time using actuator force feedback, and a coordinated control algorithm is formulated to achieve stable leveling without additional inertial or vision sensors. A full-scale field deployment demonstrated that the proposed system reduced leveling time to under three minutes and eliminated manual chain adjustments during module handling. Complementary laboratory experiments further confirmed 0.1° leveling accuracy and showed that the integrated control strategy reduced energy use and improved cable force balance compared with a conventional sequential method. These results validate the engineering feasibility of the FCLS and highlight its potential to enhance safety, precision, and automation in MC on-site installation.

Keywords -

Modular construction; Cable-driven robot; Automatic leveling, CoG estimation, Force feedback.

1 Introduction

Hong Kong faces persistent construction challenges arising from severe land scarcity, rapid population growth, and limited residential space [1]. These constraints place increasing pressure on construction efficiency, labor productivity, and site logistics. Against this backdrop, modular construction (MC) has gained increasing adoption, shifting fragmented on-site activities toward integrated and standardized off-site prefabrication with on-site installation [2][3][4]. However, on-site module installation remains highly labor-intensive, preventing further gains in installation efficiency and automation potential [5].

This limitation is particularly evident during the on-site module installation, which can be broadly divided into four sequential operations: connection, leveling, lifting, and positioning [6]. Among these operations, leveling plays a critical role, as it directly affects the structural integrity and construction quality of the installed modules. Improper leveling during placement may lead to geometric misalignment, structural damage, and additional rework. At present, leveling relies entirely on manual intervention, where experienced workers are required to stand on top of suspended modules to operate hand-chain hoists at height, as illustrated in Fig. 1. Such practices are inherently risky, inefficient, and difficult to standardize across different construction sites [7].

Figure 1. Rough chain adjustment by workers leads to module tilting and extra structural bending.

In addition to operational safety, the structural safety of the lifting frame used for module handling is equally critical [8]. The structural design and verification of such frames are typically performed under idealized assumptions, including perfectly leveled modules and symmetric force distributions at the hand-hoisting hooks that satisfy the design load conditions. However, as illustrated in Fig.1, practical installation conditions often deviate from these idealized states. The use of multiple hand-hoisting hooks, together with the CoG offsets of the suspended module, makes it difficult for workers to determine appropriate chain lengths solely through experience and coordination. Consequently, uneven load distribution among the hooks may develop, inducing unintended bending moments and localized deformation in the lifting frame. Although conservative safety margins are routinely incorporated during design to accommodate such uncertainties, these measures do not fundamentally resolve the risk during on-site operations.

In lifting and installation applications, various leveling mechanisms have been developed to improve positioning accuracy and structural safety. Actuation-based approaches (e.g., hydraulic or electric actuators) provide direct and controllable force output but face scalability challenges in modular construction due to parameter sensitivity or limited load capacity [9][10][11][12]. Alternative mechanical solutions, such as balancing-beam mechanisms with movable counterweights, achieve leveling by shifting the system's CoG but at the expense of additional heavy structural [13]. However, these methods inadequately address the on-site operational constraints of MC leveling, where manual-dependent workflows remain dominant.

In recent years, cable-driven robots (CDRs) have attracted growing interest in construction tasks requiring high positioning accuracy and flexible spatial manipulation [14]. Prior studies have reported millimeter-level installation precision [6][15], improved installation efficiency in façade assembly [16], and enhanced engineering adaptability through rational actuator reduction [17]. CDRs have also been shown to support platform leveling functions through coordinated cable actuation [18]. These characteristics indicate that CDRs are well-suited for leveling and pose adjustment tasks, where lightweight actuation and large workspace are desirable for on-site MC installation.

Despite the advances in existing approaches, several critical limitations persist in on-site leveling for MC modules. The precision control of hydraulic systems rely heavily on accurate fluid management, increasing complexity and reducing robustness. Electric linear actuators offer high accuracy but suffer from insufficient load capacity for heavy MC modules, so that relative works mostly remain at the laboratory prototype stage. Mechanical solutions like balancing beams introduce two separate moving systems for dual-axis leveling, along with significant additional weight. Furthermore, existing cable-driven robot studies lack customization for heavy-module leveling with force-feedback-based center-of-gravity estimation, leaving the algorithmic potential of CDRs—such as real-time force perception and coordinated multi-axis control—largely untapped in this context.

Motivated by these gaps, this study proposes a force-feedback cable-driven leveling system (FCLS) for MC installation, aiming to improve leveling accuracy, structural safety, and on-site operational efficiency. The proposed approach performs real-time posture estimation using actuator force feedback and generates cable motion commands to achieve stable, precise leveling during installation.

The main contributions of this work are as follows:

(1) A cable-driven leveling system structure is introduced, providing a practical and lightweight solution for force-coordinated on-site leveling of MC modules.

(2) A leveling algorithm based solely on actuator force feedback is developed, eliminating the need for additional posture or vision sensors.

(3) Physical prototypes are constructed, and both laboratory and field experiments demonstrate improved force distribution within the lifting frame, enhancing structural safety while reducing peak actuator power demand.

The remainder of the paper is organized as follows. Section 2 presents the system structure and proposed leveling algorithm. Section 3 reports laboratory and field test results. Section 4 concludes the paper and highlights directions for future research.

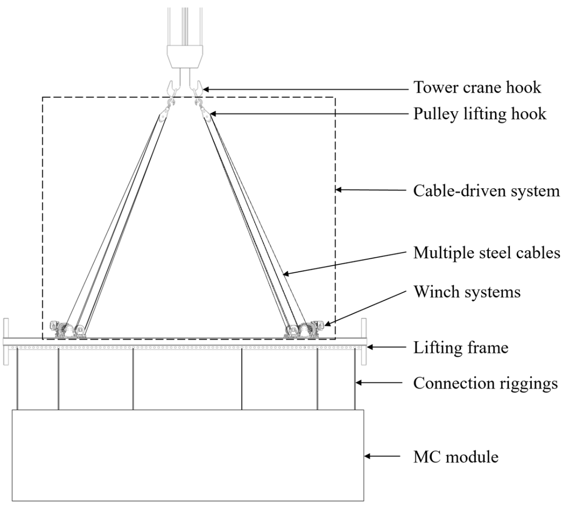
2 Force-feedback Cable-driven Leveling System (FCLS)

MC modules typically weigh 20-30 tons, and practical leveling solutions must satisfy stringent safety requirements while maintaining clear load-transfer paths throughout the handling process. These constraints impose high force capacity requirements on the cable-driven actuation system. Furthermore, uneven cable tension can adversely affect the structural safety of the lifting frame, necessitating real-time estimation of the module's CoG and coordinated cable force distribution.

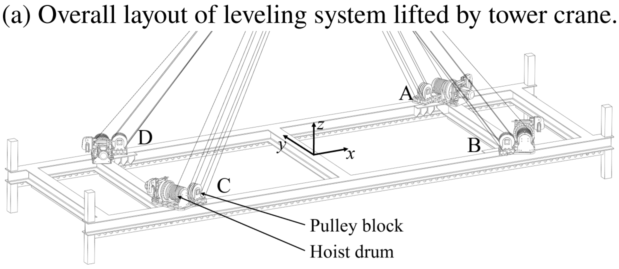
2.1 Structure design

To address the above-mentioned challenges, a cable-driven actuation structure is introduced between the crane hook and the lifting frame, enabling controllable cable length variation at each corner of the frame.

As illustrated in Fig.2, the system consists of four winch units mounted on a structural platform that interfaces directly with the crane hook. A lifting frame is suspended beneath this platform to distribute loads during lifting, while equal-length riggings connect the frame to the modular unit to ensure proper force transfer at the attachment points. Leveling is performed exclusively via the cable-driven system prior to final placement, eliminating manual intervention during installation.



(a) Overall layout of leveling system lifted by tower crane.



(b) Winch design and distribution in cable-driven system.

Figure 2. The structure design of the leveling system.

Compared with conventional leveling practices, where workers manually operate hand-chain hoists to adjust chain lengths and locking devices between the lifting frame and the module, the proposed design consolidates adjustable degrees of freedom (DoF) into a single suspended system. As a result, workers only need to connect the frame to the module without performing iterative adjustments at height, improving operational safety and consistency while reducing reliance on worker experience.

More specifically, leveling is achieved by independently adjusting the cable lengths at the four corners of the lifting frame. Each actuator drives a hoist drum to extend or retract its corresponding cable, thereby changing the frame's inclination and, consequently, the pose of the attached module. As illustrated in Fig.2(b), the cable-driven system consists of four winch units arranged at the corners of the lifting frame. Opposing actuation of specific winch pairs generates controlled roll-pitch rotation of the system. Driving winches A and B in opposition to winches C and D produces roll motion about the longitudinal axis, whereas driving winches A and D in opposition to winches B and C produces pitch motion about the transverse axis. This configuration allows simultaneous roll–pitch adjustment with minimal mechanical complexity. Fig.3 illustrates an example of the differential cable lengths generating rotational motion. To correct an initial roll tilt, the left cables are shortened ($l_1 > l_3$) while the right cables are elongated ($l_2 < l_4$), bringing the frame toward horizontal alignment. The same principle applies to pitch leveling through front-rear cable adjustment. By coordinating these differential motions, the system performs leveling as a continuous pose-correction process rather than a discrete, one-by-one manual chain adjustment.

To ensure fine pose control without imposing excessive structural demand on the system, each winch is integrated with a pulley block. The hoist drum-pulley block arrangement reduces the cable force requirement, enabling the use of smaller standardized motors and reducers, improving drum resolution, and enhancing manufacturability for heavy modular units. The pulley-assisted design therefore balances control precision with engineering feasibility.

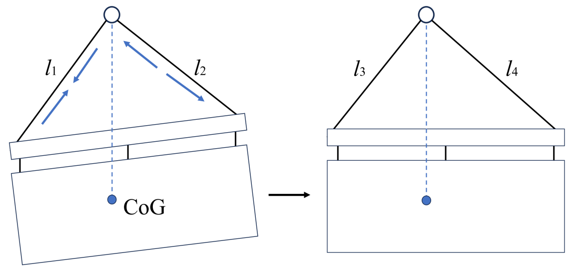


Figure 3. System rotation caused by changes in rope length.

2.2 CoG estimation for cable force coordination

With the structure introduced in Section 2.1, this section describes the force-based perception model used to estimate the system's center of gravity (CoG) position. The core task of high-precision leveling is performed during two quasi-static phases: after the initial lift-off and before the final installation, when the crane and payload are stationary. Therefore, leveling is treated as a quasi-static process in which the suspended module's total mass dominates the actuation mechanism's inertia. Under this assumption, the four cable tensions remain aligned with the gravitational direction, and the resultant force vector points in the direction of the lifting frame's spatial inclination.

Given the known geometric layout of the winch anchor points and the measured tension forces, the spatial orientation of the resultant force can be determined. This allows the CoG position to be inferred from the intersection between the resultant force direction and the vertical projection of the module's mass distribution.

To formulate the estimation model, a local coordinate system is established on the lifting frame. Let the origin be located at the geometric center of the frame, and let the four winch anchor points form a rectangle at positions A,B,C,D in this coordinate system, as shown in Fig. 2(b). The corresponding coordinates of the anchor points are expressed as

$$\begin{aligned} A &= (x, y, 0); \quad & B &= (x, -y, 0); \\ C &= (-x, -y, 0); \quad & D &= (-x, y, 0). \end{aligned} \tag{1}$$

The initial position of the hook relative to the frame coordinate system is set as P_0, which can be solved by any three of the cable lengths. With three measurable cable lengths L_A, L_B, and L_C connecting point P_0 to corners A, B, and C respectively, the local coordinates P_0 can be determined by solving the trilateration system

$$\begin{aligned} \|P_0 - A\| &= L_A; \\ \|P_0 - B\| &= L_B; \\ \|P_0 - C\| &= L_C. \end{aligned} \tag{2}$$

By solving the equation, the complete solution for P_0's coordinates (α, β, γ) is

$$\begin{aligned} &\alpha = \frac{L_C^2 - L_B^2}{4x}; \ \beta = \frac{L_B^2 - L_A^2}{4y}; \\ &\gamma = \sqrt{L_A^2 - \left(\frac{L_C^2 - L_B^2}{4x} - x\right)^2 - \left(\frac{L_B^2 - L_A^2}{4y} - y\right)^2}. \end{aligned} \tag{3}$$

With P_0 determined, the unit direction vectors are

$$\mathbf{e}_i = \frac{\mathbf{r}_i - P_0}{\|\mathbf{r}_i - P_0\|}, \quad i = A, B, C, D, \tag{4}$$

where $\mathbf{r}_i$ denotes the position vector of corner i in the local coordinate system. Given the four force magnitudes F_A, F_B, F_C, and F_D acting along the respective cables, the resultant force vector in the local coordinate system is obtained by vector summation

$$\mathbf{F}_{\text{local}} = \sum_{i=A}^{D} F_i \cdot \mathbf{e}_i. \tag{5}$$

The unit vector representing the resultant force direction is then,

$$\mathbf{n}_{\text{result}} = \frac{\mathbf{F}_{\text{local}}}{\|\mathbf{F}_{\text{local}}\|}. \tag{6}$$

Given the building information model (BIM) of the module and a given length of the connection rigging, the vertical offset between the CoG of the suspended system (frame + module) and the frame plane is denoted as h. Under the quasi-static assumption, the CoG must lie along the direction of the resultant force. Therefore, the CoG Q_0 can be expressed as

$$Q_0 = \left(\alpha - \frac{(\gamma + h)n_x}{n_z}, \ \beta - \frac{(\gamma + h)n_y}{n_z}, \ -h\right). \tag{7}$$

2.3 Leveling algorithm

The leveling control strategy aims to adaptively position the crane hook based on the perceived state of the suspended system. A distinction is made between two centers: the geometric center of the lifting frame, which is fixed, and the combined CoG of the suspended system, which varies with different module configurations. The frame's geometric center is fixed, but the combined CoG Q0 shifts with varying loads of module and attachments. The core control objective is to move the hook position above the combined CoG in the horizontal plane, thereby generating a vertical resultant force that automatically levels the entire system. Since the current hook position P0 and the unit direction vector n of the resultant force are derived in section 2.2, the target hook position for horizontal platform alignment is directly above Q_0. During leveling, the module undergoes roll–pitch rotation while remaining approximately stationary in yaw. Therefore, the hook height γ is maintained, and the target hook position is expressed as

$$P_1 = Q_0 + (0, 0, \gamma + h) = (\alpha_1, \beta_1, \gamma); \tag{8}$$

where:

$$\alpha_1 = \alpha - \frac{(\gamma + h)n_x}{n_z}, \quad \beta_1 = \beta - \frac{(\gamma + h)n_y}{n_z}. \tag{9}$$

Therefore, the new rope length should be:

$$\begin{aligned} L'_A &= \sqrt{(\alpha_1 - x)^2 + (\beta_1 - y)^2 + \gamma^2}; \\ L'_B &= \sqrt{(\alpha_1 - x)^2 + (\beta_1 + y)^2 + \gamma^2}; \\ L'_C &= \sqrt{(\alpha_1 + x)^2 + (\beta_1 + y)^2 + \gamma^2}; \\ L'_D &= \sqrt{(\alpha_1 + x)^2 + (\beta_1 - y)^2 + \gamma^2}. \end{aligned} \tag{10}$$

The required length changes for each cable are the differences from the initial lengths to the target lengths

$$\begin{aligned} \Delta L_A &= L'_A - L_A; \\ \Delta L_B &= L'_B - L_B; \\ \Delta L_C &= L'_C - L_C; \\ \Delta L_D &= L'_D - L_D. \end{aligned} \tag{11}$$

Set the adjustment time t_f and the acceleration time t_a, the algorithm shown as follows will calculate the angular velocities of the winch systems and control them to level the MC module.

Algorithm 1 Winch system movements

Data: $\Delta L_A,\ \Delta L_B,\ \Delta L_C, \Delta L_D, t_f, t_a$.
Result: $V_A(t),\ V_B(t),\ V_C(t),\ V_D(t)$
if $t_a < t < t_f - t_a$ **then**
  $V_A(t) = \Delta L_A/(t_f - t_a)$;
  $V_B(t) = \Delta L_B/(t_f - t_a)$;
  $V_C(t) = \Delta L_C/(t_f - t_a)$;
  $V_D(t) = \Delta L_D/(t_f - t_a)$;
else if $0 < t < t_a$ **then**
  $V_A(t) = t\Delta L_A/((t_f - t_a)t_a)$;
  $V_B(t) = t\Delta L_B/((t_f - t_a)t_a)$;
  $V_C(t) = t\Delta L_C/((t_f - t_a)t_a)$;
  $V_D(t) = t\Delta L_D/((t_f - t_a)t_a)$;
else if $t_f - t_a < t < t_f$ **then**
  $V_A(t) = (t_f - t)\Delta L_A/((t_f - t_a)t_a)$;
  $V_B(t) = (t_f - t)\Delta L_B/((t_f - t_a)t_a)$;
  $V_C(t) = (t_f - t)\Delta L_C/((t_f - t_a)t_a)$;
  $V_D(t) = (t_f - t)\Delta L_D/((t_f - t_a)t_a)$;
else
  $V_A(t) = V_B(t) = V_C(t) = V_D(t) = 0$

where positive values of velocities indicate cable extension, and negative values indicate cable retraction.

This adjustment moves the hook horizontally from P_0 to P_1. When the hook is aligned vertically above the combined CoG at P_1, the resultant force becomes vertical, and the frame, along with the attached module, reaches a stable horizontal orientation.

3 Experiment

This section validates the proposed FCLS through two complementary experimental phases. First, an on-site full-scale demonstration was conducted to evaluate engineering feasibility, operational workflow, and achievable leveling accuracy under real construction conditions. Second, controlled laboratory experiments were performed using a scaled prototype to quantitatively benchmark the proposed leveling algorithm against a conventional sequential leveling strategy. The evaluation metrics include leveling accuracy, adjustment time, and energy consumption.

3.1 Field application

A full-scale field demonstration was carried out on an active construction site to verify the practical feasibility and performance gains of the proposed leveling system. As shown in Fig.4, the system was deployed to hoist and level an actual MiC module, providing direct evidence of structural compatibility and on-site operability.

In conventional practice, leveling typically requires workers to repeatedly climb onto the suspended module, manually adjust chain lengths, and iteratively check levelness. In contrast, the FCLS workflow only requires workers to attach equal-length rigging chains between the lifting frame and the module. Leveling adjustments are then executed by the cable-driven system, allowing the module pose to be fine-tuned remotely while suspended. This significantly reduces high-risk work at height and improves operational consistency.

Figure 4. Onsite force-feedback cable-driven leveling system.

The results from repeated trials are summarized in Table 1. Compared with conventional manual leveling, the proposed system reduced the leveling time from 15-30 minutes to less than 3 minutes, decreased the number of ascent operations from 3-5 times to a single setup, and improved the corner height difference from less than 5 cm to less than 1 cm. These results confirm substantial improvements in efficiency, reduced exposure to high-risk manual operations, and more consistent leveling accuracy under real site conditions.

Table 1. Comparison between conventional manual leveling and the FCLS in field trials

Aspect	Tradition	Automation
Time	15-30 min	< 3min
Ascent Operations	3-5 times	1 time
Corner Height Differences	< 5cm	< 1cm

Due to on-site safety protocols, the FCLS operation was conducted in a remote manual control mode, where roll and pitch adjustments were executed sequentially. Although this stepwise operation ensured safe deployment, it does not fully exploit the system's capability for concurrent roll-pitch automation. This limitation motivates the subsequent laboratory validation of an integrated automatic control algorithm under controlled conditions.

3.2 Laboratory experiment

Laboratory experiments were conducted to quantitatively evaluate the performance of the proposed leveling algorithm and the underlying force-based perception model. A scaled experimental platform, as shown in Fig. 4, was constructed to emulate different CoG offsets between the lifting frame and the suspended payload. The CoG offset was achieved via a sliding mechanism, allowing controlled perturbations for algorithm evaluation. The system parameters are summarized in Table 2. Leveling accuracy was quantified using a calibrated gyroscope, with the angular resolution selected according to the full-scale levelness criteria.

Table 2. Parameter settings of the prototype

Parameter	Parameter explanation	Values
x	Winch distance$_x$	$0.65m$
y	Winch distance$_y$	$0.31m$
P_0	Hook position	$(0, 0, 1.25)m$
h	CoG distance	$0.3m$
M	Mass of MC	$16kg$ - $40kg$

Prior to algorithm testing, the friction characteristics of the winch systems were calibrated to ensure accurate force estimation, which is essential for the perception model. With the payload centered and cable lengths equalized, uniform retraction/extension experiments were conducted under four different loads ($16kg$, $24kg$, $32kg$, and $40kg$). The equivalent friction current was computed from the difference between the retraction and extension motor currents. The low variance of the measured currents across all loads (Table 3) demonstrates the high consistency of the current measurements, enabling a fitted friction–current relation for subsequent compensation:

$$I_{fric} = 0.07996 I_{re} + 0.4051 (R^2 = 0.9985), \quad (12)$$

where I_{fric} is the friction current calculated from the retraction current I_{re}, and R^2 is the coefficient of determination. The R-square, which is almost equal to 1, proves the rationality of linearly fitting the friction equation.

When the frame tilts, the force current of each winch motor is collected by simultaneously retracting the rope and subtracting the friction current to calculate the direction of the resultant force.

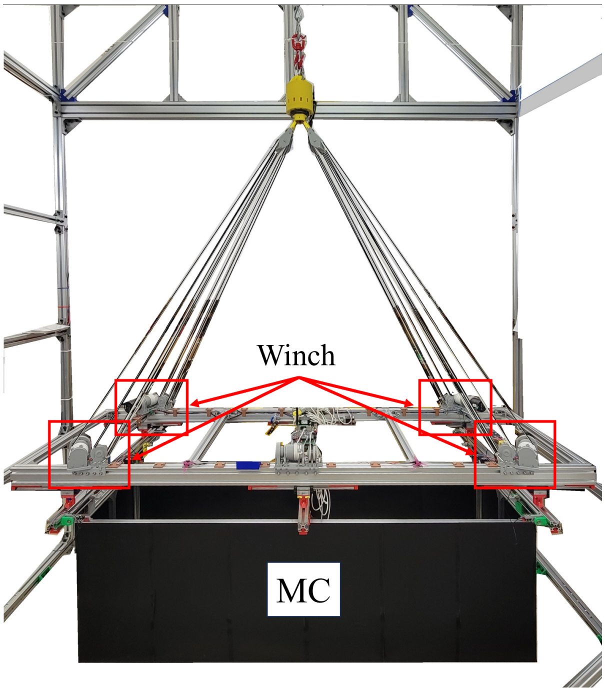


Figure 5. Laboratory prototype

Table 3. Current data of calibration

Mass of MC	Current$_{re}$	Current$_{ex}$	RMSE
$16kg$	$2.5962A$	$1.3817A$	$0.035A$
$24kg$	$3.0349A$	$1.7436A$	$0.032A$
$32kg$	$3.4636A$	$2.0861A$	$0.038A$
$40kg$	$3.8896A$	$2.4272A$	$0.042A$

Formal leveling validation was conducted in three stages. The first stage evaluated unidirectional control performance. The proposed algorithm was tested independently along the pitch and roll axes across an initial tilt range of 1°-2.5°, with ten repeated trials per axis. As summarized in Table 4, both axes achieved final angular errors below 0.1°, indicating stable convergence and consistent accuracy. The roll axis exhibited slightly larger residual errors than the pitch axis, which aligns with geometric sensitivity: roll actuation produces larger pose changes per unit cable length due to the winch layout.

Table 4. Leveling result of single direction

Direction	error$_{max}$	MAE	RMSE
Pitch	0.05°	0.025°	0.0292°
Roll	0.08°	0.036°	0.0429°

In the second stage, simultaneous pitch-roll leveling was tested to verify the integrated control strategy's core capability. The algorithm computed synchronized adjustments for all four winches to correct coupled angular deviations. As shown in Table 5, combined leveling achieved error bounds comparable to the unidirectional tests, maintaining sub-0.1° accuracy. The results confirm that the controller effectively handles cross-axis coupling and maintains stability under multi-axial disturbance conditions.

Table 5. Leveling result of compond directions

Direction	$error_{max}$	MAE	RMSE
Pitch	0.06°	0.028°	0.0335°
Roll	0.09°	0.048°	0.0535°

To show the algorithm's advantage of efficiency improvement and structure load reduction, the final stage compared the proposed integrated method with a conventional leveling approach. In this baseline method, pitch and roll adjustments are treated as two independent, sequential control loops: the pitch axis is fully leveled before correction begins on the roll axis, which requires the feedback from the gyroscope. Under identical initial conditions, the proposed method achieved the target levelness in less time and with substantially lower total energy consumption (Table 6). Besides, due to its decoupled control logic, the sequential method inherently introduced measurable cross-axis coupling effects, where active correction in the pitch axis induced unintended parasitic deviations in the roll axis, leading to oscillatory corrections to reduce errors.

Table 6. Leveling performance comparison

Approach	Time	Energy Usage
Porposed method	$60s$	$15926J$
sequential test	$91s$	$23875J$

Moreover, the baseline method produced uneven cable force distribution, concentrating approximately 54% of the total force on one diagonal and consequently imposing higher bending moment on the lifting frame. By contrast, the integrated algorithm maintained a more balanced distribution (51%), reducing peak structural demand. Collectively, these results demonstrate that the integrated control strategy not only enhances leveling speed and energy efficiency but also yields a mechanically favorable load state, which is critical for heavy modular lifting applications.

4 Conclusion

This work presented a force-feedback cable-driven leveling system for modular construction (MC) installation. The proposed system consolidates leveling adjustments into a single suspended platform and replaces manual hand-chain operations with coordinated cable control. The force-based perception model enables real-time estimation of the combined center of gravity (CoG), allowing the leveling process to be executed without additional inertial or vision sensors. A full-scale field deployment demonstrated the system's feasibility and operational benefits, including rapid leveling, elimination of high-risk adjustments at height, and improved placement consistency. Laboratory experiments showed that the integrated control strategy achieved sub-0.1° leveling accuracy and outperformed a conventional sequential method in terms of time efficiency, energy usage, and cable force balance, thereby reducing the structural demand on the lifting frame.

While the feasibility of the structure and algorithm has been validated, several directions merit further development. First, scaling the system by increasing the number of winch units could reduce peak actuator load and improve force distribution, enabling lighter frame designs or larger payloads. Second, the force-feedback scheme provides a foundation for swing suppression and disturbance compensation, suggesting the potential integration of anti-sway control for wind-induced oscillations. Third, long-term structural performance under cyclic loading remains to be investigated through finite element–based life-cycle analysis and fatigue assessment. Last but not least, due to safety considerations, fully automatic field deployment of the proposed algorithm requires comprehensive and rigorous safety validation—particularly regarding dynamic actuator effects on structural integrity and vibrations—and has therefore not yet been implemented on site. Future work will explore these directions toward robust and fully automated installation systems for industrial-scale MC deployment.

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