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Advanced Flight Control Systems: Integration of AI and Adaptive Control

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ABSTRACT

This paper presents a comprehensive study on the implementation and simulation of advanced flight control systems for Unmanned Aerial Vehicles (UAVs). The work is divided into two primary domains: the practical application of the Pixhawk Pilot Support Package (PSP) within the MATLAB/Simulink environment and the theoretical construction of a six-degree-of-freedom (6-DOF) dynamic model for fixed-wing aircraft. By leveraging the PSP, we demonstrate the integration of hardware-in-the-loop (HIL) components, including sensor fusion via uORB and actuator control. Furthermore, a high-fidelity Python-based simulation is developed to validate the 6-DOF equations of motion and control law effectiveness. This research highlights the synergistic integration of established flight control methodologies with modern simulation tools, providing a robust framework for the development and testing of advanced UAV systems. The findings contribute to the understanding of complex flight dynamics and the practical application of AI and adaptive control principles in aerospace engineering.

INTRODUCTION

The transportation of large and heavy components—such as pressure vessels, generators, and distillation columns—from fabrication sites to project locations is a critical logistical challenge in the energy, construction, and manufacturing industries (DNV GL, 2020). These modules often exceed the capacity of conventional vehicles, requiring the use of modular trailers, e.g., self-propelled modular transporters or lowbed trailers, and specially designed cargo securing lashing systems (IMO, 2011). The primary risk during such transport is cargo shifting, which can cause vehicle instability, infrastructure damage, worker injury, or even death (Kusuma, 2008).

Several standards and codes of practice have been developed to ensure the safety of lashing systems. In the maritime sector, the International Maritime Organization (IMO) published the Code of Safe Practice for Cargo Stowage and Securing (CSS Code), which provides a methodology for calculating the force balance on non-standard cargoes (IMO, 2011). For integrated marine and onshore transport operations, DNVGL-ST-N001 (DNV GL, 2020) is the primary reference for designing lashing systems. This standard requires that the total securing force be greater than the sliding force, accounting for appropriate safety factors.

Previous research has extensively examined lashing systems for maritime transport. Zhang et al. (2022) developed an evidential reasoning approach for stowage optimization on multipurpose vessels. Liu et al. (2021) conducted numerical and experimental analyses of lashing forces on cylindrical cargo securing systems aboard ships. Wang et al. (2020) investigated the effect of lashing configuration on load distribution in container securing systems. However, research specifically addressing lashing systems for onshore heavy module transportation remains limited. Onshore transport has different dynamic loading characteristics, including acceleration, deceleration, and centrifugal forces during cornering, as well as varying road conditions (Kreuzer & Kloo, 2015). Therefore, validation of lashing systems against relevant standards is essential.

The objectives of this study are: (1) to evaluate the conformity of a lashing system used in an onshore heavy module transport project with DNVGL-ST-N001 and the IMO CSS Code; (2) to calculate the securing and sliding forces under various operating conditions; and (3) to provide recommendations for improvement or optimization if necessary.

METHOD

Module and Transport System Description

This study was conducted to examine the onshore transportation process of a pressure vessel with specific technical specifications that constitute the primary object of analysis. The module in question has a total weight of 5,000 kg, equivalent to 5 metric tons, with a length of 6 meters and a diameter of 2 meters. This geometric configuration results in a relatively high length-to-diameter (slenderness) ratio, meaning that the load distribution and support points during the loading and transport processes must be carefully evaluated to prevent excessive deflection or localized stress concentration on the vessel shell, consistent with structural transportation analyses performed on large pressure vessels such as shell-and-tube heat exchangers under transit loading conditions (Predictive Engineering, n.d.), and in accordance with established design and evaluation standards for pressure vessel structures (ASME, n.d.). The transportation of the module is planned using a lowbed trailer equipped with a flat steel deck, selected for its capacity to withstand heavy loads while providing a stable, level platform for the placement and securing (lashing) of cylindrical cargo such as pressure vessels. The selection of this transport mode is consistent with common practice in the oil and gas as well as heavy construction industries, where lowbed trailers are frequently employed to transport oversized and overweight equipment requiring high stability throughout overland travel. In this context, transportation safety is a critical consideration, as inadequate securing systems or improper load calculations may result in cargo displacement, vehicle instability, or even structural damage during transit (Melnyk et al., 2024). Proper sizing and verification of the lashing system are therefore essential, as supporting and lashing forces acting on cargo during transport have been shown to significantly influence overall cargo stability and safety (Wang et al., 2024), while tension analysis of lashing components using finite element methods further provides a basis for ensuring that securing devices can withstand dynamic loading without failure during road transport (Sága & Jakubovičová, 2023). The static friction coefficient between the module and the trailer deck (μ) was taken as 0.3, representing a steel-to-steel, dry and clean contact condition (IMO, 2011).

Lashing System Configuration

The evaluated lashing system consisted of four chain lashings arranged to secure the module against displacement during transport, with each chain specified to have a Working Load Limit (WLL) of 1.5 metric tons. The chains were positioned at a horizontal inclination angle (α) of 30° relative to the horizontal plane and a transverse angle (β) of 20° relative to the longitudinal axis of the trailer, forming a diagonal lashing arrangement intended to restrain the load in both the longitudinal and transverse directions simultaneously. This configuration is consistent with the diagonal (over-top or cross) lashing method prescribed by the EN 12195-1 standard for the calculation of lashing forces, which stipulates that the securing force generated by the lashings must counteract the inertia force acting on the load, since friction alone is generally insufficient to prevent sliding under dynamic loading conditions encountered during road transport (European Committee for Standardization [CEN], 2010). In accordance with this approach, the required securing forces are determined by resolving the lashing tension into its components along both the longitudinal (x) and transverse (y) axes of the load, which corresponds directly to the horizontal and transverse angles applied in the present lashing configuration (Lerher, 2015). A safety factor of 2.0 was applied to the chain lashing system per standard requirements, providing a margin against unexpected dynamic loading such as sudden braking, acceleration, or cornering forces during transit; this practice aligns with general cargo-securing principles in which load-securing chains are commonly assigned a safety factor representing the ratio between breaking strength and working load limit, with typical values ranging between three and four depending on the chain grade and the governing regulatory framework (Federal Motor Carrier Safety Administration [FMCSA], n.d.), although a lower factor may be considered acceptable in lashing applications where the consequence of failure differs from that of overhead lifting. To ensure symmetrical load distribution and prevent eccentric loading on the module, two chains were installed on the left side and two on the right side of the vessel in a mirrored configuration, with each chain anchored to dedicated lashing points integrated into the trailer deck structure. This symmetrical four-point arrangement reflects standard practice in diagonal lashing design, where at least four lashing systems are required to secure cargo against both tipping and sliding, and where the resulting lashing capacity together with the applied vertical and horizontal angles determines the overall effectiveness of the securing arrangement (REMA Holland B.V., n.d.). The selection of a relatively low transverse angle in combination with the specified horizontal angle was further evaluated in light of known limitations within the EN 12195-1 framework, as prior research has demonstrated that the standard's calculation method for lashing forces can yield disproportionately high, or even mathematically unreasonable, demands for the required number of lashings at certain critical angle combinations (Jagelčák, 2022), underscoring the importance of verifying lashing angle selection against both the standard formulae and sound engineering judgment.

Force Calculation Methodology

The analysis followed the methodology established in IMO CSS Code Annex 13 (IMO, 2011) and DNVGL-ST-N001 Section 6 (DNV GL, 2020), both of which provide internationally recognized frameworks for assessing the adequacy of cargo securing arrangements for non-standardized and project cargo. Annex 13 of the CSS Code sets out an advanced calculation method intended to verify whether a given lashing arrangement is sufficient to withstand the external forces acting on a cargo unit during transport, since standard vessel lashing systems are generally not designed to accommodate oversized or non-standardized items such as heavy project cargo (Kaps, n.d.). Under this method, the external forces acting on the cargo in the longitudinal, transverse, and vertical directions are derived from basic acceleration data tabulated according to vessel characteristics, and are subsequently resolved through the vertical securing angle (α) and horizontal securing angle (β) of each lashing device, with correction factors applied to account for the combined contribution of each lashing to both the longitudinal and transverse restraining forces (IMO, 2011). This calculation procedure was directly applicable to the present case, given that the four-chain lashing configuration employed in this study was likewise defined by a vertical angle α of 30° and a horizontal angle β of 20°, consistent with the angle-based force resolution approach prescribed by the Annex. In parallel, DNVGL-ST-N001 was applied to verify the broader marine and transport operation aspects of the lashing arrangement, as this standard constitutes the principal industry reference for the design and execution of marine operations, including loadout, sea transport, and road transport of heavy or oversized cargo, and prescribes minimum material and safety factors for securing equipment such as shackles, turnbuckles, and chain or web lashing assemblies (DNV GL, 2020). The combined application of both references allowed the lashing system to be evaluated not only against the force-balance principles defined by the IMO CSS Code but also against the more conservative structural and operational safety margins required under DNV's marine

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warranty practice, thereby providing a more comprehensive and cross-validated assessment of the securing arrangement's adequacy for the intended transport condition.

Sliding Force

The total sliding force acting on the module was determined from the maximum accelerations expected in the longitudinal and transverse directions during onshore transport, in line with the acceleration-based force assessment approach adopted in cargo securing standards (DNV GL, 2020). In the longitudinal direction, the sliding force Fx arises primarily from emergency braking deceleration or sudden acceleration of the trailer, with a maximum deceleration ax of 0.8 g commonly adopted as a standard design value for onshore cargo transport (DNV GL, 2020). Applying this value to the module mass of 5,000 kg yields $Fx = m \times ax = 5{,}000 \times 0.8 \times 9.81 = 39{,}240$ N, equivalent to approximately 4.00 MT. In the transverse direction, the sliding force Fy results from centrifugal effects generated when the vehicle negotiates a turn, with a maximum centrifugal acceleration ay of 0.5 g representative of a sharp cornering maneuver (DNV GL, 2020). This produces a transverse force of $Fy = m \times ay = 5{,}000 \times 0.5 \times 9.81 = 24{,}525$ N, or approximately 2.50 MT. These two force components form the basis against which the adequacy of the lashing arrangement is subsequently evaluated.

Securing Force

The total securing force resisting the calculated sliding forces was derived from two contributing mechanisms: the friction force generated between the module and the trailer deck, and the restraining force provided by the chain lashing system. The friction force was calculated as $F\_fric = \mu \times m \times g = 0.3 \times 5{,}000 \times 9.81 = 14{,}715$ N, or approximately 1.50 MT, using a friction coefficient of 0.3, a value consistent with that commonly applied for timber-on-steel or comparable dunnage-to-deck contact conditions in established cargo securing guidance (North of England P&I Association, n.d.). The contribution of the chain lashing system was evaluated separately, with each of the four chains rated at a Working Load Limit (WLL) of 1.5 MT. Consistent with the vector-based force resolution method described in IMO CSS Code Annex 13, in which the restraining contribution of each securing device is resolved according to its vertical angle α and horizontal angle β, the effective longitudinal and transverse components of each chain were obtained through trigonometric projection (IMO, 2011). In the longitudinal direction, all four chains were considered to contribute simultaneously, giving a total chain restraining force of $CS\_x,total = 4 \times WLL \times \cos\alpha \times \cos\beta = 4 \times 1.5 \times \cos 30° \times \cos 20° = 4 \times 1.5 \times 0.866 \times 0.94 = 4 \times 1.22 = 4.88$ MT. In the transverse direction, only the two chains installed on the left side were assumed to actively resist a rightward sliding force, with each chain contributing $WLL \times \cos\alpha \times \sin\beta = 1.5 \times 0.866 \times 0.342 = 0.44$ MT, yielding a combined contribution of $2 \times 0.44 = 0.88$ MT from the two left-side chains.

Total Securing Force and Safety Ratio

The total restraining force, $F\_restraint$, was obtained by summing the friction force and the chain lashing force in each respective direction, and was then compared against the corresponding sliding force to obtain a safety ratio, with a value greater than 1.0 indicating compliance with standard securing requirements (IMO, 2011; DNV GL, 2020). In the longitudinal direction, the total restraining force was calculated as $F\_restraint,x = F\_fric + CS\_x,total = 1.50 + 4.88 = 6.38$ MT, giving a safety ratio of 6.38 / 4.00 = 1.60, which exceeds the required minimum of 1.0 and is therefore considered compliant. In the transverse direction, however, the initial configuration produced a total restraining force of $F\_restraint,y = F\_fric + CS\_y,total = 1.50 + 0.88 = 2.38$ MT, resulting in a safety ratio of 2.38 / 2.50 = 0.95, which falls below the required threshold and is therefore non-compliant. Because the initial arrangement failed to satisfy the transverse safety requirement, two additional cross lashings were introduced at a vertical angle of 45° and a horizontal angle of 60°, in accordance with the principle that supplementary diagonal lashings can be added to increase transverse restraining capacity when an initial configuration proves insufficient (IMO, 2011). The additional transverse restraining contribution from these two cross lashings was calculated as $CS\_y,added = 2 \times 1.5 \times \cos 45° \times \sin 60° = 2 \times 1.5 \times 0.707 \times 0.866 = 2 \times 0.92 = 1.84$ MT, giving a revised total transverse restraining force of $F\_restraint,y,new = 2.38 + 1.84 = 4.22$ MT. This corresponds to a new safety ratio of 4.22 / 2.50 = 1.69, which exceeds the required minimum of 1.0 and confirms that the revised configuration is compliant. The results

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presented below summarize the final, optimized securing system arrived at through this iterative verification process.

RESULTS AND DISCUSSIONS

Results

Sliding and Securing Forces

Table 1 summarizes the sliding and securing forces for the longitudinal and transverse directions after optimization. In the longitudinal direction, the sliding force was 4.00 MT, while the total securing force was 6.38 MT. In the transverse direction, the sliding force was 2.50 MT, and the total securing force was 4.22 MT.

Table 1. *Comparison of sliding and securing forces.*

Parameter	Longitudinal Direction	Transverse Direction
Sliding Force (Fx / Fy) [MT]	4.00	2.50
Friction Force (F_fric) [MT]	1.50	1.50
Chain Lashing Force (CS) [MT]	4.88	2.72
Total Securing Force [MT]	6.38	4.22
Safety Ratio	1.60	1.69

Contribution Analysis

In the longitudinal direction, chain lashings contributed 76.5% (4.88 of 6.38 MT) of the total securing force, while friction contributed only 23.5%. In the transverse direction, chain lashings contributed 64.5%, and friction contributed 35.5%. This indicates that the lashing system relies heavily on the strength and configuration of the chains, especially for resisting transverse forces.

Compliance with Standards

According to the IMO CSS Code, the minimum required safety ratio is 1.0 for quasi-static conditions (IMO, 2011). DNVGL-ST-N001 includes additional dynamic safety factors, but for direct comparison, a ratio greater than 1.0 satisfies the basic criteria (DNV GL, 2020). With safety ratios of 1.60 longitudinal and 1.69 transverse, the optimized lashing system meets international safety requirements.

Discussion

The results demonstrate that the initial lashing system without cross lashings was inadequate to resist transverse sliding forces during cornering. A centrifugal acceleration of 0.5 g produced a transverse sliding force of 2.50 MT, while the initial securing force was only 2.38 MT (ratio 0.95). This inadequacy was primarily due to the shallow lashing angle β = 20°, which resulted in a very small transverse component (only 0.44 MT per two chains). This finding is consistent with Chen et al. (2019), who stated that the lashing angle is the most critical parameter in cargo securing system design.

Adding two cross lashings with a steeper angle (60° to the transverse plane) effectively increased the transverse securing capacity by 1.84 MT, raising the total to 4.22 MT (safety ratio 1.69). This result aligns with the IMO CSS Code Appendix 4, which emphasizes the importance of asymmetrical securing arrangements and optimal lashing angles (IMO, 2011). In practice, cross lashings are commonly used for tall cargoes such as pressure vessels because their center of mass is above the trailer deck (IMO, 2011).

The friction force contributed only 1.50 MT due to the low steel-to-steel friction coefficient (0.3). Wang et al. (2020) noted that increasing the friction coefficient using rubber mats can raise friction to 0.4–0.45. For future transport operations, high-friction materials are recommended to reduce reliance on chain lashings.

This study has several limitations. First, the analysis assumed static maximum accelerations (0.8 g and 0.5 g) without accounting for dynamic factors such as road-induced vibrations or shock loading. Second, no field experimental validation with load cells was conducted. However, Liu et al. (2021) showed that the difference between numerical and experimental lashing forces is within 9–10%, so this method is sufficiently accurate for preliminary design.

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The practical implication is that transport operators must perform quantitative calculations for each heavy module shipment, rather than relying solely on standard practices or experience. Lashing configurations must be tailored to the direction of the greatest force (typically transverse). Regular inspection of chain condition (wear, corrosion) and lashing points is also essential, as actual strength degrades over time (Kusuma, 2008).

CONCLUSIONS

Based on the quantitative analysis of a lashing system for onshore heavy module transportation, the following conclusions are drawn. The analysis demonstrated that the initial lashing system, comprising four conventional chains, was inadequate for resisting transverse loading, yielding a safety ratio of 0.95, below the required minimum of 1.0. Following the introduction of two additional cross lashings, the optimized configuration achieved total securing forces of 6.38 MT in the longitudinal direction and 4.22 MT in the transverse direction, corresponding to safety ratios of 1.60 and 1.69, respectively, both of which satisfy the requirements of the IMO CSS Code and DNVGL-ST-N001. Friction was found to contribute only 23.5% of the total securing force in the longitudinal direction and 35.5% in the transverse direction, indicating that the overall restraining capacity of the system depends predominantly on the strength and configuration of the chain lashings rather than on frictional resistance alone. On this basis, the optimized lashing system can be considered safe and applicable to similar onshore transport operations involving modules of comparable weight and dimensions. Nevertheless, since the present analysis was based on static force-balance calculations, future research should incorporate field validation using load cells installed on the lashing chains and accelerometers mounted on the cargo, in order to verify the theoretical results and to account for dynamic effects such as road-induced vibration, shock loading, and transient acceleration that may not be fully captured by static analytical methods.

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