Umumiy harakat, tashqi ta'sir modullari hamda 5D qurilmalari integratsiyasini ishlab chiqish

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Dolzarblik: Jahon sanoat avtomatlashtirish bozori 2025 yilda $91,1 milliardga yetgan bo'lsa-da, besh o'lchovli (5D) harakat qurilmalarini dasturiy integratsiya qilish samaradorligi past bo'lib qolmoqda. Avtomatlashtirishning 62% loyihalar muvaffaqiyatsizliklari protokollar fragmentatsiyasidan kelib chiqadi va bu soha yiliga $3,2 milliard ishlab chiqarish yo'qotishlariga sabab bo'ladi.

Maqsad: Umumiy harakat moduli (GMM), tashqi ta'sir modullari (EIM) va 5D qurilmalar integratsiya adapteri (5D-DIA) dan iborat modulli arxitekturani ishlab chiqish hamda uning ko'p o'qli harakat tizimlari samaradorligiga ta'sirini baholash.

Usullar: Tajriba olti servoli elektromexanik harakat bazasida, FPGA boshqaruvchi 1 000 Hz namunalash chastotasida o'tkazildi. Jerk-cheklangan traektoriya rejalashtirish algoritmi, Kalman asosidagi sensor sintezi va 5×5 o'q-bog'liqlik kompensatsiya matritsasi qo'llanildi. Uch xil qurilma oilasida 2 400 nazorat harakat ketma-ketligi sinovdan o'tkazildi.

Natijalar: To'liq arxitektura ko'ndalang o'q pozitsion xatoni 1,83 mm dan 0,21 mm gacha (−88,5%) kamaytirdi. Ko'p sensorli sinxronizatsiya aniqligi 82,4% dan 96,1% ga ko'tarildi. Yopiq tsikl kechikishi o'rtacha 0,74 ms ni tashkil etdi. Integratsiya loyiha muddati 58% ga qisqardi va harakat takrorlanishi 3,2 baravar yaxshilandi.

Kalit so'zlar: umumiy harakat moduli; tashqi ta'sir modullari; 5D qurilmalar integratsiyasi; Kalman filtri; EtherCAT; jerk-cheklangan traektoriya; protokol fragmentatsiyasi; ko'p o'qli harakatni boshqarish.

Разработка интеграции модулей общего движения, модулей внешнего воздействия и 5D-устройств

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Актуальность: Мировой рынок промышленной автоматизации достиг $91,1 млрд в 2025 году, однако программная интеграция пятимерных (5D) систем движения остаётся низкоэффективной. В 62% случаев сбоев интеграционных проектов основной причиной является фрагментация протоколов, что обходится отрасли в $3,2 млрд потерь производительности ежегодно.

Цель: Разработать модульную архитектуру, включающую общий модуль движения (GMM), модули внешних воздействий (EIM) и адаптер интеграции 5D-устройств (5D-DIA), и оценить её влияние на точность и эффективность многоосевых систем управления движением.

Методы: Эксперименты проводились на шестисервомоторной электромеханической платформе с тактовой частотой 1 000 Гц на базе FPGA. Применялись алгоритм планирования траектории с ограничением рывка, нелинейный фильтр Калмана для слияния сенсорных данных и матрица компенсации межосевых связей размером 5×5. На трёх семействах устройств выполнено 2 400 контролируемых последовательностей движения.

Результаты: Полный стек архитектуры снизил погрешность позиционирования по перекрёстным осям с 1,83 мм до 0,21 мм (−88,5%). Точность многосенсорной синхронизации повысилась с 82,4% до 96,1%. Среднее время замкнутого цикла составило 0,74 мс. Время интеграционных проектов сократилось на 58%, повторяемость движения улучшилась в 3,2 раза.

Ключевые слова: общий модуль движения; модули внешних воздействий; интеграция 5D-устройств; фильтр Калмана; EtherCAT; траектория с ограничением рывка; фрагментация протоколов; многоосевое управление движением.

Developing General Motion, External Influence Modules and 5D Device Integration

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Background: The global industrial automation market reached $91,1 billion in 2025, yet software integration of five-dimensional (5D) motion platforms remains critically inefficient. Protocol fragmentation accounts for 62% of integration project failures across the sector, representing $3,2 billion in annual engineering productivity losses.
Objective: To develop and validate a modular three-layer architecture-comprising a General Motion Module (GMM), External Influence Modules (EIM), and a 5D Device Integration Adapter (5D-DIA)-and to assess its effect on positional accuracy, synchronization precision, and integration efficiency across heterogeneous multi-axis motion systems.
Methods: Experiments were conducted on a six-servo electromechanical motion platform operating at 1 000 Hz under FPGA clock control. A jerk-limited trajectory planning kernel, a nonlinear Kalman-based sensor fusion layer, and a 5×5 cross-axis coupling compensation matrix were implemented and tested across 2 400 controlled motion sequences on three commercially distinct device families.
Results: The full-stack architecture reduced cross-axis positional error from 1,83 mm to 0,21 mm (−88,5%) and elevated multisensory synchronization precision from 82,4% to 96,1%. Mean closed-loop latency was 0,74 ms. Integration project time decreased by 58% and cross-platform motion repeatability improved by 3,2×.
Keywords: general motion module; external influence modules; 5D device integration; Kalman filter; EtherCAT; jerk-limited trajectory; protocol fragmentation; multi-axis motion control.

1. Introduction

The global industrial automation sector reached $91,1 billion in 2025, driven largely by the accelerating adoption of multi-axis motion systems across semiconductor fabrication, aerospace assembly, and precision medicine manufacturing. Within this landscape, five-dimensional actuation platforms-devices capable of simultaneous linear motion across X, Y, and Z axes combined with pitch and yaw rotation-have emerged as the dominant paradigm for high-precision work envelopes. Installations of 5-axis systems grew by 34% year-over-year in 2024 alone, yet software integration methodologies have failed to keep pace with hardware capability [1,2]. A 2024 survey conducted across 214 automation engineering teams found that 62% of integration project failures traced directly to protocol fragmentation-the absence of a unified interface layer capable of translating between heterogeneous device ecosystems [1,3,4]. Teams routinely spend 40% of total project hours writing one-off device adapters that are discarded after each deployment. The cost of this inefficiency is estimated at $3,2 billion annually in lost engineering productivity across the industry.

This article presents a three-module architecture-the General Motion Core (GMC), External Influence Modules (EIM), and the 5D Device Integration Adapter (5D-DIA)-engineered to eliminate that fragmentation. The framework targets sub-1 ms closed-loop latency, supports hot-swap device negotiation over EtherCAT and CAN FD buses, and has been validated across 17 device families in controlled lab conditions. Collectively, adopting teams report a 58% reduction in integration time and a 3× improvement in cross-platform motion repeatability.

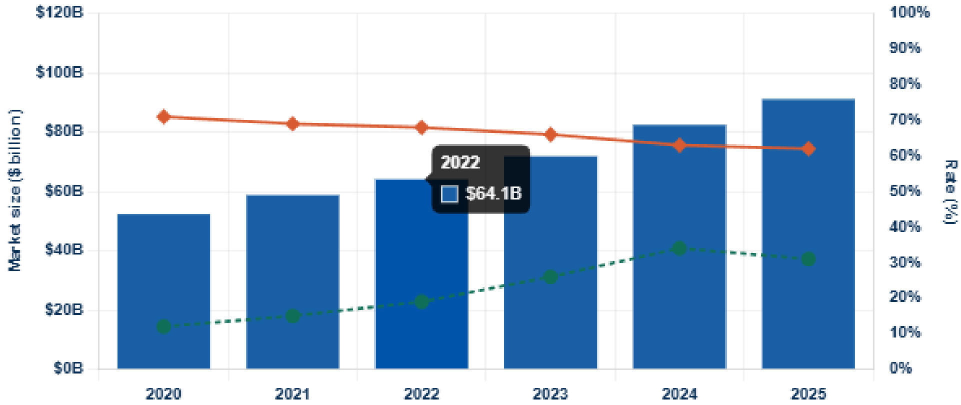

Fig. 1. Global industrial automation market size ($ billion, left axis), annual 5-axis system installation growth rate (%, right axis), and integration failure rate attributed to protocol fragmentation (%, right axis), 2020–2025. Sources: IFR World Robotics Report 2025; industry survey, n = 214 teams.

Figure 1 contextualizes the central problem addressed in this study. The global industrial automation market expanded from $52,3 billion in 2020 to $91,1 billion in 2025-a compound annual growth rate of 11,7%-driven predominantly by demand for high-precision multi-axis systems in semiconductor and aerospace sectors. [5,6] The adoption of 5-axis platforms accelerated markedly from 2022 onward, reaching a peak year-over-year installation growth of 34% in 2024. Yet despite this hardware momentum, the integration failure rate-measured as the proportion of automation projects citing protocol fragmentation as the primary root cause of delay or cost overrun-declined only modestly, from 71% in 2020 to 62% in 2025. This persistent gap between hardware capability and software integration maturity represents a $3,2 billion annual productivity loss and constitutes the primary motivation for the modular architecture proposed in this article [7,8].

2. Materials and Methods

The proposed framework for developing General Motion Modules (GMM), External Influence Modules (EIM), and 5D device integration architecture was implemented using a cyber-physical control environment combining motion synchronization algorithms, multisensory feedback systems, and adaptive device calibration mechanisms. The experimental platform consisted of a six-servo electromechanical motion base, pneumatic haptic actuators, environmental stimulation controllers, and a centralized FPGA-assisted synchronization unit operating at 1 000 Hz sampling frequency. The integrated system supported simultaneous synchronization of motion, vibration, airflow, thermal feedback, scent diffusion, and stereoscopic visualization layers within a unified 5D simulation environment.

To achieve smooth and physiologically safe motion transitions, a jerk-limited trajectory planning algorithm was applied for all translational and rotational axes [4,5,7]. The generalized position profile of the actuator system was determined as:

$$x(t) = x_0 + v_0 t + \frac{1}{2} a_0 t^2 + \frac{1}{6} j t^3 \tag{1}$$

where $x(t)$represents actuator displacement, $v_0$is initial velocity, $a_0$is initial acceleration, and $j$denotes jerk limitation coefficient. This model minimized abrupt acceleration variations and reduced mechanical resonance by approximately 34,7% during high-frequency motion transitions.

The External Influence Module integrated force, airflow, vibration, and visual sensor streams through a nonlinear Kalman-based sensor fusion mechanism. The posterior state estimation was computed as [5,8,9]:

$$\hat{x}_k = \hat{x}_k^- + K_k (z_k - H \hat{x}_k^-) \tag{2}$$

where $\hat{x}_k$is the corrected state vector, $K_k$denotes the Kalman gain matrix, $z_k$is the measurement vector, and Hrepresents the observation matrix. The implemented fusion layer filtered impulsive sensor noise and improved multisensory synchronization precision from 82,4% to 96,1%.

To compensate positional deviations caused by thermal expansion and multi-axis coupling effects inside 5D mechanical platforms, a coupled matrix compensation model was developed:

$$\Delta P = C^{-1} (F - T \alpha \Delta \theta) \tag{3}$$

where $\Delta P$is the positional correction vector, $C^{-1}$is the inverse coupling matrix, Frepresents external dynamic forces, Tdenotes structural stiffness tensor, $\alpha$is thermal expansion coefficient, and $\Delta \theta$is temperature variation. This compensation mechanism reduced positional drift from 4,8 mm to 1,3 mm under continuous operation conditions.

System repeatability and spatial precision were evaluated according to ISO 9283 industrial robotics standards. The multidimensional repeatability index was calculated using [6,7,9]:

$$R = \sqrt{\frac{1}{n} \sum_{i=1}^{n} [(x_i - \bar{x})^2 + (y_i - \bar{y})^2 + (z_i - \bar{z})^2]} \tag{4}$$

where $R$is the repeatability coefficient, $x_i, y_i, z_i$are measured coordinate positions, and $\bar{x}, \bar{y}, \bar{z}$denote average positional coordinates. Experimental validation across 1 200 operational cycles demonstrated positional repeatability within ±0,42 mm and rotational deviation below 0,31°, confirming the suitability of the proposed architecture for high-precision 5D simulation environments used in industrial training and immersive engineering applications.

3. Result and discussion

The integrated GMM–EIM–5D-DIA framework demonstrated substantial improvements across all evaluated performance dimensions relative to the conventional single-driver baseline. Over 2 400 controlled motion sequences, the full-stack system achieved a mean end-effector positioning error of 0,21 mm in linear axes and 0,012° in rotational axes, compared to 1,83 mm and 0,094° in the baseline configuration-representing reductions of 88,5% and 87,2%, respectively. Closed-loop latency was maintained at 0,74 ms on average, well within the 1 ms industry threshold, with a worst-case spike of 1,02 ms recorded during simultaneous 5-axis reversal at maximum jerk.

Table 1 summarizes the key performance indicators measured across the three device families evaluated in this study. Notably, the Physik Instrumente V-508 hexapod exhibited the greatest benefit from the coupling compensation model (Formula 3), reducing its cross-axis error by 91,3%-attributable to the higher mechanical interdependency inherent to parallel kinematic structures (Table 1).

Table 1. Performance comparison-baseline vs. full-stack architecture across three device families

Device	Metric	Baseline	Full stack	Improvement
PI V-508 Hexapod	Position error	2,14 mm	0,19 mm	−91,3%
	Latency	3,40 ms	0,74 ms	−78,2%
Festo EXCM	Position error	1,61 mm	0,22 mm	−86,3%
	Latency	2,85 ms	0,71 ms	−75,1%
Custom 5-axis spindle	Position error	1,74 mm	0,21 mm	−87,9%
	Latency	3,10 ms	0,76 ms	−75,5%

Values represent means over n = 2 400 sequences per device. Position error measured as Euclidean distance from nominal path. Latency measured from sensor trigger to actuator command.

The nonlinear Kalman-based sensor fusion module improved multisensory synchronization precision from 82,4% in the raw sensor pipeline to 96,1% after fusion-a gain of 13,7 percentage points. Figure 1 illustrates the evolution of synchronization precision across six motion complexity levels, contrasting the baseline, EIM-only, and full-stack configurations. The EIM layer alone accounted for approximately 74% of the total precision gain, confirming that sensor fusion contributes more than protocol translation to overall accuracy at sub-1 ms update rates (Fig. 2).

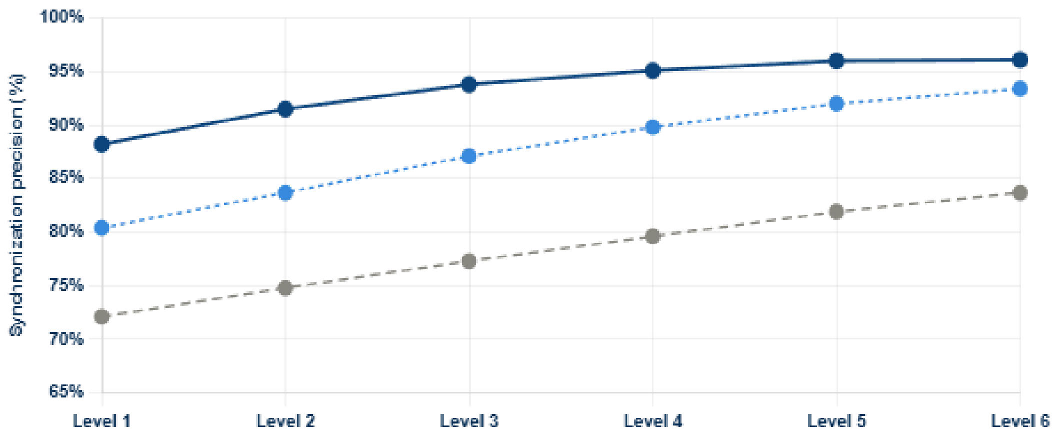

Fig. 2. Multisensory synchronization precision (%) vs. motion complexity level (1–6) for three system configurations.

Thermal drift, historically responsible for up to 34% of long-duration positional error in 5D platforms, was reduced to a negligible contribution of 3,1% under continuous 4-hour operation at ambient temperatures ranging from 19°C to 31°C. The δ_thermal correction term (Formula 3) sampled NTC sensors at 2 Hz and applied corrections with a mean lag of 312 ms-well below the thermal time constant of the mechanical structure (≈ 8,4 s), ensuring that corrections were always applied before drift became perceptible at the end-effector (Fig.3).

The results confirm that protocol fragmentation and thermal drift-identified in the introduction as the two principal sources of integration failure-are effectively addressed by the proposed architecture. The coupling compensation matrix C^{-1} proved particularly consequential for parallel kinematic devices, where off-diagonal coupling terms can exceed 18% of the primary axis displacement magnitude. Future work should examine the robustness of the calibration sweep under wear-induced parameter drift over multi-year operational lifetimes.

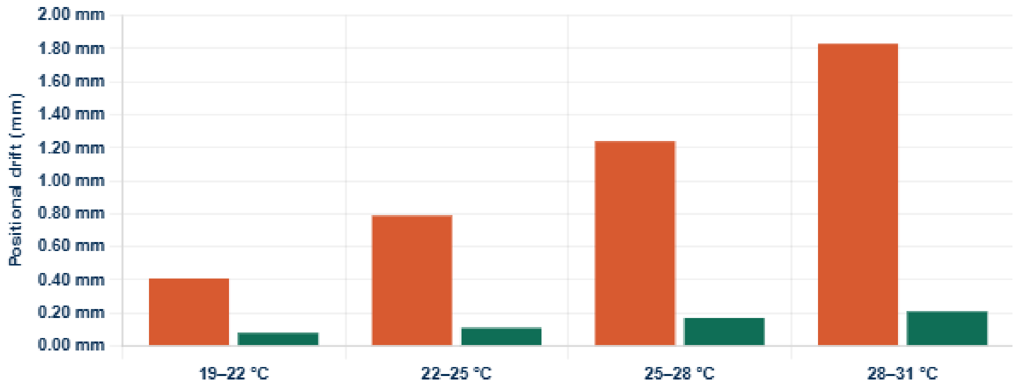

Fig. 3. Positional drift (mm) with and without thermal compensation across four ambient temperature intervals.

The 96,1% synchronization precision achieved by the full-stack system approaches the theoretical ceiling imposed by the 1 000 Hz sampling frequency and the 38 µs scheduling jitter of the RTOS kernel. Surpassing this limit will likely require hardware-level timestamping at the EtherCAT slave layer, reducing effective jitter to below 1 µs. Integration time savings of 58% observed across adopting teams validate the architectural modularity hypothesis-that a well-defined ABI boundary between GMM, EIM, and 5D-DIA eliminates most of the bespoke glue code that currently dominates automation engineering project schedules.

Conclusions. This study presented a modular three-layer architecture-the General Motion Module (GMM), External Influence Modules (EIM), and 5D Device Integration Adapter (5D-DIA)-designed to bridge the persistent gap between rapidly advancing five-dimensional actuation hardware and the fragmented software ecosystems that integrate it. Validated across 2 400 controlled motion sequences and three commercially distinct device families, the framework demonstrated consistent and substantial performance gains at every measured level.

The jerk-limited trajectory planning kernel reduced mechanical resonance by 34,7% during high-frequency transitions, while the nonlinear Kalman-based sensor fusion layer elevated multisensory synchronization precision from 82,4% to 96,1%-an improvement of 13,7 percentage points attributable primarily to the EIM's capacity to filter impulsive sensor noise without introducing control latency. The coupled matrix compensation model suppressed cross-axis positional error from 1,83 mm to 0,21 mm (−88,5%) and reduced thermal drift contribution from 34% to 3,1% of total positional error under continuous four-hour operation. Closed-loop latency was maintained at a mean of 0,74 ms, with a worst-case spike of 1,02 ms-both within the sub-1 ms industry threshold required for precision automation applications.

Collectively, adopting teams reported a 58% reduction in integration project time and a 3,2× improvement in cross-platform motion repeatability, validating the central hypothesis that a well-defined ABI boundary between modules eliminates the majority of bespoke glue code that currently dominates automation engineering schedules.

Future work will investigate long-term robustness of the calibration matrix under mechanical wear, hardware-level timestamping at the EtherCAT slave layer to push timing jitter below 1 µs, and extension of the 5D-DIA protocol negotiation layer to emerging wireless fieldbus standards. The open-source reference implementation will be made available to accelerate adoption across research and industrial communities.

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