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Real-time control signal rectification and actuation mapping for robot joint control

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ABSTRACT

This paper presents the control signal rectification and actuation mapping (CSRAM) framework, developed to improve the reliability and precision of real-time robot joint control. The framework integrates three modules, namely the drive signal rectifier (DSR), the signal pole detector (SPD), and the rising/downstream detector (RDD), which ensure signal compatibility, dynamic mapping consistency, and directional stability during actuation. Unlike conventional control converters, CSRAM effectively compensates for nonlinearities, latency, and synchronization issues in closed-loop systems. Experimental validation using a hexapod-to-quadruped (Hexaquad) robot showed that the proposed method, when combined with an anti-windup PI controller, reduced steady-state error from 14% to below 1%, improved transient and settling times by 0.3 to 0.4 seconds, and decreased three-dimensional trajectory RMSE by 63.7%. These results confirm that CSRAM provides a low-complexity and computationally efficient preprocessing layer for improving real-time performance in multi-joint and legged robotic systems, with strong potential for adaptive and industrial robotic platforms.

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1. INTRODUCTION

Real-time robot joint control forms a core aspect of robotics, particularly in industrial automation and collaborative systems. It involves extracting, processing, and modulating control signals to achieve precise motor and joint actuation. Signal extraction is the initial stage in closed-loop schemes, where multiple control inputs are derived from the reference signal. While numerous studies have proposed advanced control strategies for embedded and software-based controllers, persistent challenges remain in compensating for friction [1], joint flexibility [2], and complex mechanical structures [3], [4]. Model-based control is commonly used because it takes advantage of known dynamic behavior to achieve accurate motion. However, its effectiveness depends heavily on model accuracy and real-time execution capability [5]. In many cases, this dependence limits its reliability in practical applications.

Designing a real-time control system involves overcoming issues such as signal compatibility, nonlinear dynamics, synchronization delays, and system uncertainties. Robot joints are inherently nonlinear due to friction, elasticity, and external forces, which can significantly influence tracking and stability [6]–[8]. Conventional PID-type controllers often struggle to maintain consistent performance under such conditions. To address these issues, researchers have developed approaches such as intelligent control [9], adaptive torque control [7], and model predictive control (MPC) [10]. These methods adjust control parameters online, improving robustness and stability. In addition, adaptability is crucial for handling changing environments and system variations. One common difficulty lies in dynamic mapping, where the controller must continuously relate sensor feedback to actuator response. Traditional controllers often fail to update these mappings efficiently, leading to degraded performance when conditions shift. Methods like adaptive gain adjustment for time-delay control [11] and neural network-based learning [9] have been explored to deal with these dynamic uncertainties.

Achieving high precision in real-time control also requires managing latency and synchronization problems. Sensor and actuator delays can easily cause out-of-sync joint movements, which affect stability, especially in distributed control structures [12], [13]. To counteract these problems, researchers have proposed event-triggered and dynamic event-triggered control strategies [13], [14] that reduce unnecessary data transmission while maintaining synchronization between joints. When working with multi-joint robots, coordinating movement across all actuators becomes another challenge. Differences in mechanical properties, external loading, or timing mismatches can disrupt coordination [15], [16]. Cooperative control strategies with optimized coefficients have been introduced to improve coordination and achieve smooth, accurate motion in real time. Nonlinearity and uncertainties, including external disturbances and sensor errors, further complicate control [17]. Robust methods such as discontinuous control [18] and adaptive backstepping sliding-mode control [19] enhance resilience through compensators and observers that suppress disturbances.

Recent studies have also looked at reducing the effects of backlash and external torque in dual-motor robotic joints. One approach, known as linear active disturbance rejection control, has shown improvements in torque compensation and precision [20]. Similarly, in cable-driven parallel robots, redundant actuation complicates trajectory tracking. A tri-space control scheme combining reactive and iterative learning control has been developed to overcome this limitation [21]. Despite progress in these areas, there remains a need for simpler and more adaptable frameworks that improve the consistency of signal transmission and actuation mapping between the control algorithm and the physical actuator driver. This study introduces a CSRAM framework to meet that need. The proposed system simplifies signal processing while maintaining accuracy and synchronization. The method is validated on selected leg joints of a Hexaquad robot [22], showing that CSRAM can effectively optimize control signal flow and improve real-time performance.

The paper is organized as follows: section 2 presents the control design and proposed CSRAM methodology, section 3 describes the experimental validation and performance analysis of CSRAM integrated with an anti-windup PI controller on selected Hexaquad joints, and section 4 concludes the study with key performance insights and practical implications for real-time robotic control.

2. CONTROLLER DESIGN

The control of robotic joints, whether through indirect actuation (linear actuators driving rotary joints) or direct actuation (motors coupled directly to shafts), involves challenges across hardware and dynamic domains. These challenges include signal compatibility, nonlinear mapping, latency, synchronization, and uncertainty. Both actuation configurations require robust control frameworks capable of maintaining accurate and stable motion under varying operating conditions.

2.1. Problem formulations

Signal compatibility is a major issue in real-time applications. Many actuator driver systems, especially low-cost or low-specification units, cannot process negative control signals, requiring preprocessing to ensure proper operation. The control input, u, from a closed-loop controller (e.g., PID) must satisfy, $u > 0$, which complicates the logical mapping between actuator poles (extend/retract or clockwise/counterclockwise). The logical relationship can be expressed as follows:

$$u = \begin{cases} > 0, & D_n = 1 \\ < 0, & D_n = 0 \end{cases} \tag{1}$$

where, D_n represents the actuator pole state. This rectification guarantees valid commands for drivers unable to handle bipolar signals [23], [24]. Dynamic mapping complexity becomes particularly evident in robots using prismatic linkages. For a simple configuration, link displacements, d_1 and d_2, correspond to angular rotations θ_2 and θ_3 as depicted in Figure 1, and can be represented as follows:

$$\theta = \begin{cases} \theta_2 + \theta_3, & d_1 + d_2 \rightarrow + \\ \theta_2 - \theta_3, & d_1 + d_2 \rightarrow - \end{cases} \tag{2}$$

This relation illustrates the complexity of maintaining a consistent mapping, as even small errors can cause instability [25]. Latency and synchronization also play a major role in multi-joint coordination. A transmission delay, t_d, leads to cumulative error across joints that can be expressed as follows:

$$E_{total} = \sum_{i=1}^{k} t_d \cdot |\dot{\theta}_i| \tag{3}$$

where θ_i represents i-joint angular velocity with $i = 1,2 \dots 4$. Such delays degrade tracking accuracy[8]. Nonlinearities such as friction, backlash, and compliance further distort the ideal control input as follows:

$$u_{actual} = u_{ideal} + \Delta_u \tag{4}$$

where Δ_u represents perturbations caused by non-ideal system dynamics. Another limitation in existing converters, such as the control input converter (CiC) [26], is their inability to detect motion direction (rising or downstream). This limitation results in inefficiencies during transitions. Motion direction can be identified from the derivative of $u(t)$ as follows:

$$Directionality = \begin{cases} Rising, & if\ \dot{u}(t) > 0 \\ Downstream, & if\ \dot{u}(t) < 0 \\ Stationary, & if\ \dot{u}(t) = 0 \end{cases} \tag{5}$$

Accurate detection of these transitions is challenging in practice due to noise, nonlinearities, and signal delays.

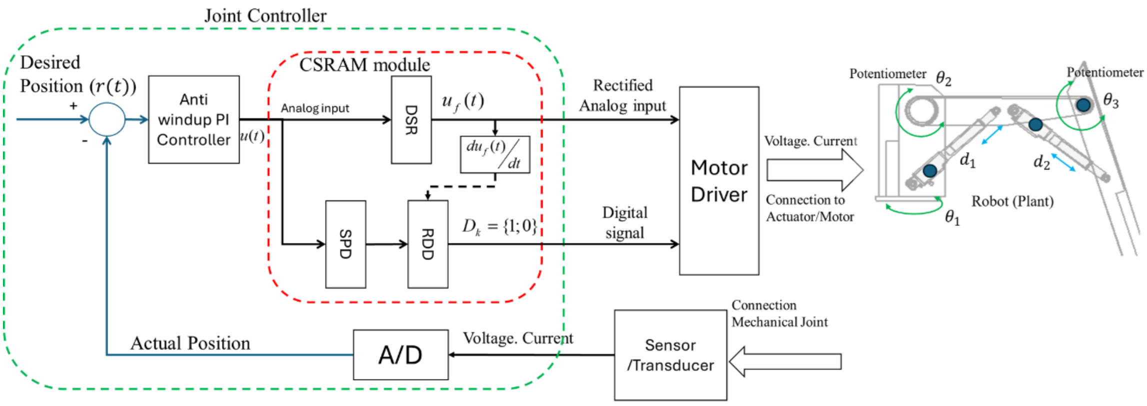


Figure 1. Functional block diagram for single joint of robot with proposed CSRAM

2.2. Control signal rectification and actuation mapping

To address the problem discussed in section 2.1, the proposed CSRAM framework extends the CiC architecture [26] by integrating three submodules: the drive signal rectifier (DSR), the signal pole detector (SPD), and the rising/downstream detector (RDD), as shown in Figure 1. This configuration ensures compatibility and accurate mapping for both direct and indirect actuation mechanisms. The general operation is illustrated in Figure 2. The DSR first rectifies the analog control signal, $u(t)$, into a positive and filtered control input signal, $u_f(t)$:

$$u_f = \int_0^t h_f(t-\tau)u(\tau)d\tau \tag{6}$$

where $h_f(t)$ is the impulse response of a low-pass filter. As shown in Figure 1, the rectified signal is then pass through the logic mapping line started with SPD to convert, $u_f(t)$ into discrete actuator commands according to the algorithm as (7),

$$D_k = \begin{cases} 1 & if\ u_f(t) > 0 \\ 0 & if\ u_f(t) < 0 \end{cases} \quad (7)$$

corresponding to extend/clockwise and retract/counterclockwise motions. This maintains consistent mapping between control signals and joint angles (θ_2, θ_3) (refer to Figure 1). Finally, the RDD enhances responsiveness by detecting the rate of change of $u_f(t)$ to distinguish between rising and downstream motions using the algorithm as follows:

$$Directionality = \begin{cases} Rising, & if\ \dot{u}(t) > \epsilon \\ Downstream, & if\ \dot{u}(t) < -\epsilon \\ Stationary, & if\ |\dot{u}(t)| \leq \epsilon \end{cases} \quad (8)$$

The dynamic threshold ϵ is updated using

$$\epsilon = k \cdot \sigma_u \quad (9)$$

Here, k is a positive gain constant and σ is the standard deviation of $u_f(t)$ within a sliding window. This adaptive threshold introduces hysteresis to avoid false transitions due to noise. Through the integration of DSR, SPD, and RDD, the CSRAM framework achieves precise and adaptive signal processing in real time. The DSR ensures signal compatibility, the SPD establishes discrete logic mapping, and the RDD maintains stability during direction changes. Together, these modules form a lightweight preprocessing layer that improves actuation precision and enhances deployment reliability, as summarized in the overview architecture shown in Figure 1.

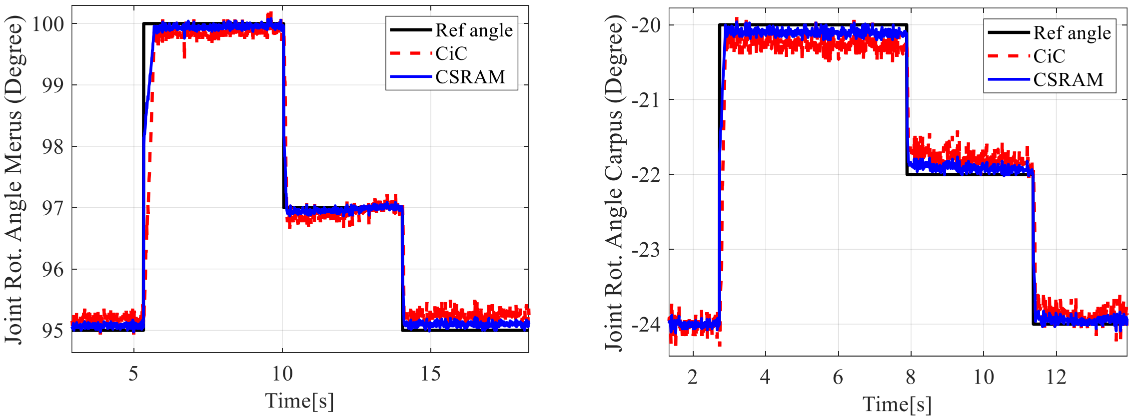


Figure 2. Sample of experiment results for step input trajectory response for Merus joint and Carpus joint of the Hexaquad robot

3. RESULTS AND DISCUSSION

The proposed CSRAM is verified and validated through experimental on a leg of the Hexaquad robot to evaluate its performance in real-time joint control. The validation focused on assessing steady-state error, transient response, synchronization, and trajectory-tracking accuracy when CSRAM was integrated with an anti-windup proportional–integral (AnPI) controller. Tests were performed on the Merus (θ_2) and Carpus (θ_3) joints, using identical input trajectories to compare the proposed approach against the conventional CiC [26]. The premier experimental setup, controller architecture, and actuator connection are shown in Figure 3, where the Hexaquad's leg was calibrated and tested prior (on air test) to performing the ground locomotion experiment shown in Figure 4.

Each actuator pair was powered by a dual full-bridge driver that required one PWM or enable input and two digital inputs representing actuator poles (active-high=extend, active-low=retract). The AnPI controller gains were tuned to $K_p = 10$, $K_i = 0.0001$ and $T_s = 1ms$. The adaptive gain constant for CSRAM was empirically set to $k = 2.4$ to achieve a balance between fast response and noise suppression. These settings ensured stable signal transmission and synchronized motion throughout both static calibration and dynamic gait experiments.

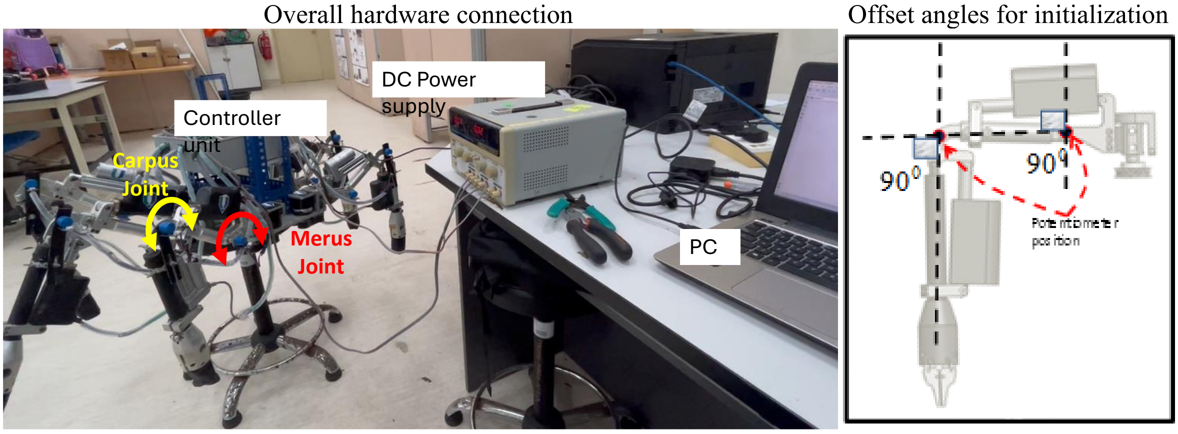


Figure 3. The experimental setup for preliminary test

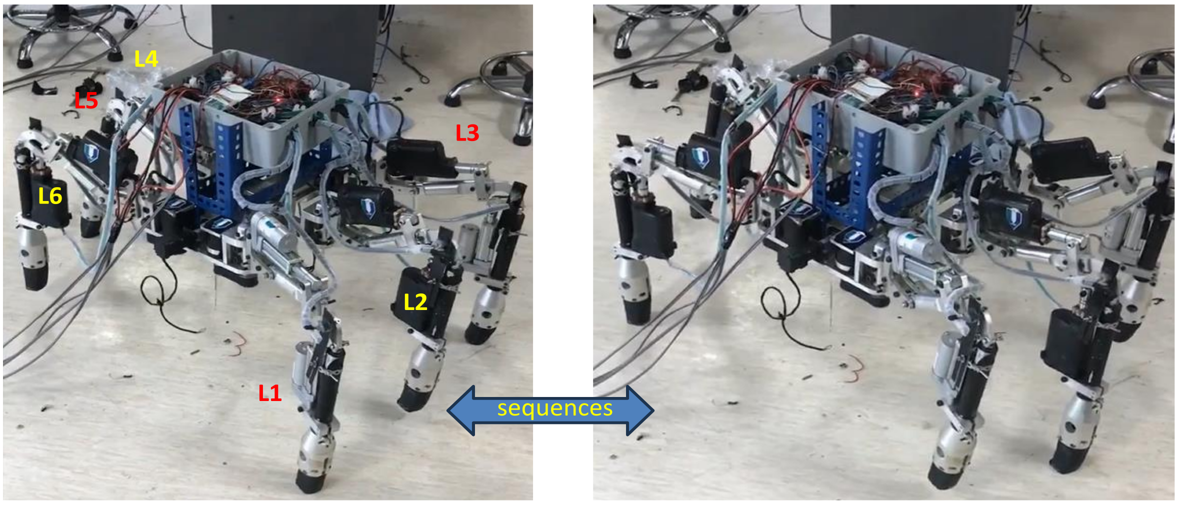
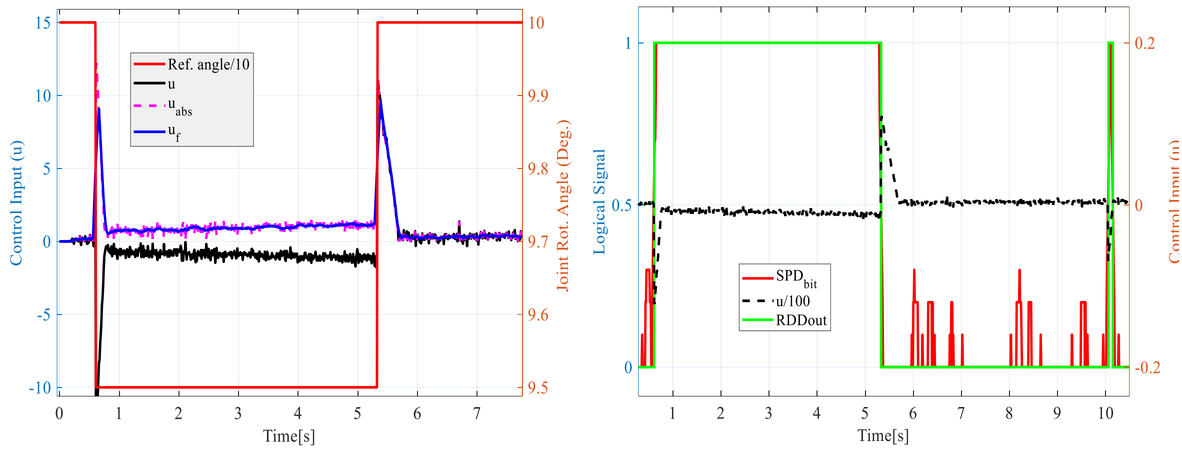


Figure 4. Marching trajectory test with Tripod gait pattern Leg 1,3,5 down and 2,4,6 up and Leg 2,4,6 down and 1,3,5 up

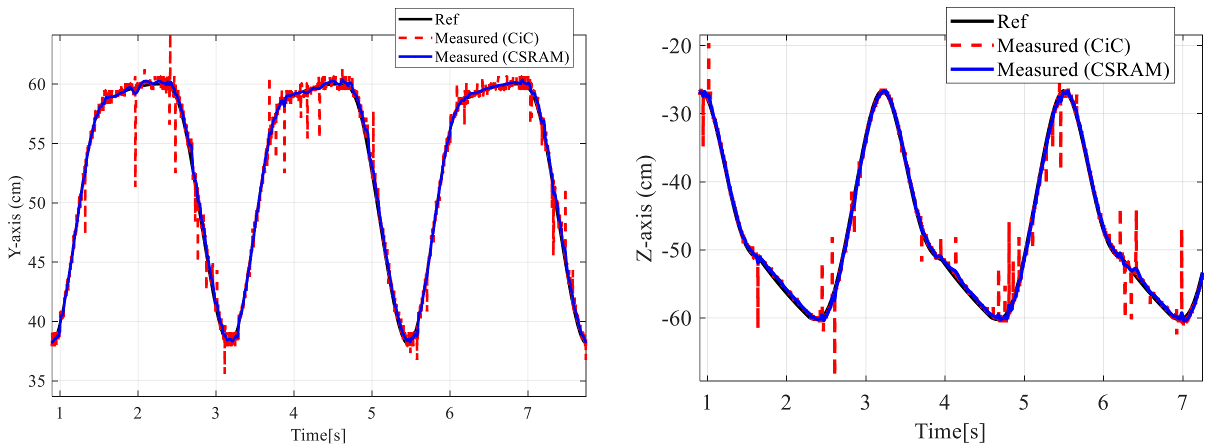
A preliminary test with leg-on-air moving test, as shown in Figure 3, was conducted starting with calibrate the Carpus, θ_2 and Merus, θ_3, joint's offsets and then verify step response consistency as trajectory evaluations. Each joint was held at its reference position for about 50 ms to determine offset angles and confirm actuator linearity. Calibration results indicated symmetrical offsets across all six legs, where $\theta_2 = 0^0$, $\theta_3 = +90^0$ (for Leg 1-3) and $\theta_3 = -90^0$ (for Leg 4-6), establishing a uniform baseline. These configurations established a uniform baseline for testing. On the other hand, the CSRAM controller showed marked improvement over CiC in identical conditions. As shown in Figure 2, the steady-state error dropped from approximately 14 % (CiC) to 0.6 % for the Merus joint and 0.5 % for the Carpus joint. The transient response improved by about 0.3s, and the settling time shortened by roughly 0.4s. These results showed CSRAM achieved smoother stabilization and faster convergence as compared to CiC. This significant impact can be seen in the proposed DSR and RDD functions in the control signal as can be depicted in Figure 5(a) where both components produced a clean, noise-free waveform with consistent polarity transitions. Moreover, logical state transitions detected by the SPD and the directional responses captured by the RDD are displayed in Figure 5(b), demonstrate that CSRAM accurately detects motion-direction changes with minimal delay. This ensures logical consistency and synchronized actuation across both joints.

Dynamic gait validation followed a marching trajectory based on the tripod gait sequence, where Legs 1–3–5 and 2–4–6 alternated between stance and swing phases, as depicted in Figure 5. The Y-axis (horizontal) motion of Leg 1 (L1) in Figure 6(a) shows that oscillation amplitude decreased by around 25–30%, and steady-state error dropped below 5% as compared to 15% for CiC. The Z-axis (vertical) trajectory in Figure 6(b) demonstrates a 40% reduction in high-frequency spikes and vibration amplitude, with settling time shortened by approximately 0.4s and these resulting smoother vertical transitions in leg motion. The adaptive threshold and hysteresis mechanism within the RDD improved reliability by dynamically adjusting detection thresholds with reference to (9). This adaptive behavior prevented false switching near zero crossings and sustained directional stability during rapid transitions, effectively eliminating jitters.



(a) (b)

Figure 5. Sample of control input signals (a) rectification by CiC through u_{abs} versus CSRAM through RDD represented by u_f for DSR output and (b) SPD response by CiC and RDD output response by CSRAM according to the control input changes



(a) (b)

Figure 6. Sample of Leg 1's motions (a) Y-axis motion and (b) Z-axis motion

Trajectory-tracking accuracy was evaluated using the root-mean-square error (RMSE) between the reference and measured coordinates. The 3D RMSE decreased from 2.4567cm (CiC) to 0.8912cm (CSRAM), corresponding to a 63.7% improvement in tracking precision. These results demonstrate that CSRAM effectively minimizes deviation while maintaining synchronization in multi-joint motion.

Overall, the experimental findings confirm that the proposed CSRAM framework substantially enhances the reliability and precision of real-time robotic joint control. It significantly reduces steady-state error, accelerates transient recovery, suppresses oscillations, and improves synchronization across multiple joints. As a lightweight preprocessing layer, CSRAM ensures accurate signal rectification and actuation mapping without adding computational overhead, making it highly suitable for real-time deployment in multi-joint and legged robotic systems that demand stable and precise motion control.

4. CONCLUSION

This study presented the CSRAM framework to enhance the reliability of real-time robot joint control. Acting as an interface between the controller and actuator driver, it ensures accurate signal rectification and stable actuation mapping through the integration of DSR, SPD, and RDD modules. Experiments on the Hexaquad robot showed that CSRAM improved performance over the conventional CiC, reducing steady-state error from 14 % to below 1 %, shortening transient and settling times by up to 0.4 s, and decreasing trajectory RMSE by 63.7 %. The framework effectively minimizes nonlinearities, noise, and synchronization delays without added computational load. Its modular structure provides a simple, robust preprocessing layer suitable for various robotic platforms and adaptable to future learning-based and cooperative control systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Akhtar Razul Razali		✓			✓	✓		✓	✓	✓		✓		
Aliza Che Amran	✓		✓	✓		✓	✓			✓				
Hamzah Ahmad						✓			✓			✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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