

Article

RM-Act 2.0: A Modular Harmonic Actuator Towards Improved Torque Density

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Abstract

In modern robotics, actuator performance is fundamental to achieving efficient and durable motion, with compactness and torque density being especially critical. Compact actuators enable integration in space-constrained systems without compromising functionality, while high torque density ensures powerful output relative to size, enhancing efficiency and versatility. Harmonic gearboxes embody these qualities, offering lightweight design, zero backlash, and excellent torque density, which have made them a standard choice in robotics. However, their widespread adoption is limited by high manufacturing costs due to the precision machining required. To address this challenge, the authors previously introduced RM-Act, a Radial Modular Actuator employing two synchronous belts as harmonic speed reducers. Building on this concept, RM-Act 2.0 is introduced as an improved version that employs a single synchronous belt. This design reduces transmission slippage, improves torque density, and offers greater modularity with a wider range of reduction ratios. The work details the development and validation of RM-Act 2.0 through a functional prototype and performance model, highlighting its advancements over the original RM-Act in compactness and torque density.

Keywords: actuators; harmonic drive; torque density; synchronous belts; robots



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1. Introduction

Actuators are pivotal in modern robotics, serving as the key components that enable motion and interaction with the environment by converting energy into mechanical force or movement. They constitute actuation mechanisms with a power source and torque-transmitting elements encased in a housing, while the output is delivered through a shaft or linkage. Robotic actuators further employ feedback and control elements to fine-tune the output quality to the desired level. General robotic platforms employ electrical motors equipped with mechanical transmissions, as they are comparatively smaller, easy to control, and less prone to mechanical losses [1].

Rotary actuators with electric motors, featuring fixed or variable compliance, higher torque density, and precision, have the potential to dominate industrial and medical robotics. Their advanced capabilities make them ideal for applications requiring efficiency and accuracy. Lightweight and compact designs are particularly advantageous for these application. For mobile robotic systems, lower weight means higher autonomy, particularly

from cobots to assistive devices [2], being compact brings advantages in maneuverability and interaction comfort [3].

That said, most industrial robots employ transmission technologies such as Harmonic Gearboxes (HGs), Planetary Gear Trains (PGTs), and Cycloid Drives (CDs), which are relatively uncommon in other industries [4].

PGTs are commonly employed in robotic systems where compactness, efficiency, and moderate torque transmission are required [5]. Their coaxial input–output configuration enables high power density and balanced load distribution, making them ideal for applications where space and weight constraints are critical. For example, in legged [6,7], legged-wheeled [8,9], and legged-tracked [10] robots, PGTs are frequently integrated into joint and wheel actuators to achieve efficient torque transmission while maintaining low inertia, thereby improving dynamic response and motion control. Their smooth operation and backdrivability make them suitable for robots that require compliant or force-sensitive interactions with the environment, such as hybrid mobility platforms capable of both rolling and stepping. Beyond locomotion, PGTs are also utilized in robotic manipulators, humanoids, and space mechanisms, where precise, reliable, and lightweight actuation is essential. Owing to their versatility and manufacturability, PGTs continue to serve as a fundamental choice for moderate-torque robotic joints and drive modules. HGs were able to replace the conventional PGTs from many applications, particularly after a major improvement of the performance resulting from a new teeth geometry introduced by [11] in the 90's—which also improved its stiffness linearity. Furthermore, HG's shape is characterized by larger diameters than lengths, while the weights are substantially lower than for other technologies and result in the best torque-to-weight ratios [4].

Being lighter than cycloidal drives (CDs) and offering inherent compliance [12], along with the potential for higher speed reduction ratios and excellent repeatability, harmonic gears (HGs) continue to dominate robotic actuation systems [13–15]. They are also extensively used in exoskeletons, where high torque output is crucial. For instance, ANYdrive used in ANYmal legged robots utilizes a HG with an electric motor to actuate legs for locomotion [16]. Kang et al. [17] developed a SEA-based exoskeleton featuring high-fidelity closed-loop torque control, while Font-Llagunes et al. [18] introduced a lightweight and modular robotic exoskeleton to assist walking after spinal cord injury. Further advancements include the integration of shape memory alloys for joint torque estimation in harmonic drive systems [19] and the use of cycloidal gears in robotic knee joints [2]. Moreover, HGs have found applications in space robotics, where precision and compactness are vital [20]. Most flexspline (FS) and circular spline (CS) gear profiles are nearly conjugate and non-involute in nature [21]. However, several studies have sought to develop fully conjugate gear pairs with purely involute profiles [22,23]. Another related concept is the Vernier drive a high-ratio involute gear reducer that leverages the Vernier effect to achieve large transmission ratios [24]. That being said, the complex machining and monopoly of HGs have made them costlier, both for availability and maintenance. In addition, the flexible element demanded either greater radial development or length which resulted in a dead volume affecting the torque-to volume ratio. While the concept of HGs is well established, researchers are still advancing and tailoring this technology to meet the demands of modern robotics, particularly for achieving high torque density and precision [25,26].

It is noteworthy, as per [4], along with the physical volume, the actual shape of the actuator also plays a key role, and tends to have a larger impact on the system's compactness. This also means that the actuator should have a lesser number of components [27]. Several studies have focused on enhancing torque density through both motor and gearbox design optimizations. Some works emphasize improvements in motor architecture to achieve higher torque output and efficiency. For instance, Galea et al. [28] discussed strategies

such as employing cobalt–iron laminations, adopting open-slot designs, implementing Halbach arrays, and using unequal stator teeth to increase torque density while minimizing losses. Recent advancements in motor control and design offer potential pathways to enhance control accuracy, torque consistency, and torque density in actuators like RM-Act 2.0. Studies on variable phase-pole machines show that optimizing current distributions during pole transitions maintains constant torque while minimizing stator copper losses, thereby improving torque density and energy efficiency [29]. Meanwhile, model-free predictive control using ultra-local models with fixed-time observers and extremum-seeking adaptation improves transient response and reduces current fluctuations [30], and robust MPC frameworks employing cascaded EKF–LESO structures enable encoderless operation with strong disturbance rejection [31]. Complementary research efforts have explored novel transmission mechanisms, such as magnetic gearboxes, which enable contactless torque transfer and improved efficiency through magnetic coupling [32]. For gear-based drives, Shin et al. [33] proposed a low-backlash, high-backdrivable planetary gearbox that enhances torque density by optimizing gear tooth geometry and minimizing frictional losses, leading to smoother and more efficient power transmission. Building upon these advances, the present work focuses on improving the torque density of HGs through refined mechanical design and performance optimization. Though HGs possess fewer parts when compared to other transmission systems, the flexible element is most prone to overheating and impulse torques. Many approaches address this issue with the flexspline while integrating the Harmonic actuation. A most recent approach presents a new harmonic movable tooth drive that replaces small module teeth with rigid movable teeth featuring a logarithmic spiral profile, allowing near-surface contact under load for improved performance [34]. Most of the FS and CS are nearly conjugate and noninvolute, but there are also some studies attempting to prepare fully conjugate gear pairs of purely involute profiles [21–23].

Furthermore, the overheating and impulse torques experienced by the flexspline make it unsuitable for applications requiring lower speed reduction ratios. As reported in the literature [4], the transmission ratio strongly influences the performance of robotic systems. Although HGs are widely used for their precision and torque density, the range of single-stage transmission ratios is typically limited to values greater than 30:1. Consequently, robotic platforms that demand a speed reduction ratio below 30 are unable to fully benefit from harmonic actuation, which represents a notable limitation.

Recognizing the flexspline as a critical component in harmonic gears (HG) and ensuring system modularity can significantly enhance their versatility, streamline the replacement of failed components, and broaden the design scope of harmonic actuators for specialized applications.

Numerous studies [35–37] have highlighted the potential of rapid prototyping techniques in advancing harmonic actuator development, with [37] being particularly notable for its innovative use of a 3D-printed flexspline. Building upon this foundation, the authors in their previous work [38] introduced the RM-Act, which utilizes synchronous belts and other commercially available components to achieve a speed reduction ratio of 9:1. This design, employing a synchronous belt as the flexspline, offers improved capability for handling fluctuating torque and enables straightforward replacement in case of component failure.

With its novel design approach in harmonic actuation, the RM-Act concept effectively addresses several of the aforementioned concerns; however, it has not primarily focused on enhancing the torque density of the system. The overall design criteria should therefore shift more strongly toward improving parameters such as weight, volume, and efficiency. In this regard, minimizing the dead volume within the actuator and developing a lightweight yet robust structure to maintain optimal belt tension are crucial. Additionally, mitigating

slippage would extend the range of payload handling and enhance system transparency by reducing transmission stage losses [39].

This paper aims to enhance torque density while preserving the advantages of harmonic actuation, offering the following key contributions: (i) the introduction of a novel single-stage speed reducer that utilizes a single synchronous belt functioning as a harmonic speed reducer; (ii) a detailed explanation of the underlying actuation mechanism; (iii) the development of the Radial Modular Actuator (RM-Act 2.0) using predominantly commercially available components, thereby minimizing machining requirements; (iv) experimental evaluation of the actuator prototype through model identification tests; and (v) a comprehensive analysis of its performance improvements over the original RM-Act design.

Otto, a lightweight quadruped robot weighing 8 kg and featuring 8 degrees of freedom (DOFs) [40], could benefit significantly from the integration of lightweight abduction–adduction joint actuators. The RM-Act actuator was developed to meet this requirement, and RM-Act 2.0 represents a refined iteration of this concept, offering superior torque density and enhanced overall performance.

The remainder of this paper is organized as follows: Section 2 introduces the concept of the proposed design; Section 3 details the finalized design, including the CAD model and component specifications; Section 4 presents the static and dynamic test results; Section 5 discusses the model identification outcomes and final parameter estimation of RM-Act 2.0; Section 6 compares the performance characteristics of RM-Act and RM-Act 2.0; and finally, Section 7 concludes the paper with a discussion on future research directions.

2. Concept of the Design

The working principle of the proposed RM-Act 2.0 design is analogous to that of the RM-Act [38], which operates similarly to a harmonic gearbox (HG). Typically, an HG comprises three main components: an elliptical bearing, referred to as the strain wave generator (SWG), which serves as the input; a deformable external gear known as the flex-spline (FS), whose one end functions as the output; and a stationary internal gear called the circular spline (CS), which possesses t additional teeth compared to the flex-spline.

Let the number of teeth on the flex-spline and circular spline be denoted by N_f and N_o , respectively. Then,

$$t = N_f - N_o. \quad (1)$$

The speed reduction ratio is given as

$$s = \frac{-t}{N_o}. \quad (2)$$

Like [38], the proposed design of RM-Act 2.0 introduces a cost-effective harmonic speed reducer by employing commercially available components. In this design, the flex-spline (FS) is replaced with a timing belt, while the circular spline (CS) is substituted with an external gear. A pair of idler pulleys (IPs), driven by a motor, move in a circular orbit and act as the wave generator (WG) by deforming the timing belt.

In RM-Act 2.0, the timing belt loops around two central pulleys, one fixed pulley (FP) and one movable output pulley (OP), both coaxial with the rotational axis of the IPs. Similar to a traditional harmonic gearbox (Figure 1c), the stationary and movable pulleys possess nearly identical tooth counts, N_f and N_o , differing only by a small value t . The timing belt's active engagement regions are shared between the stationary and movable pulleys.

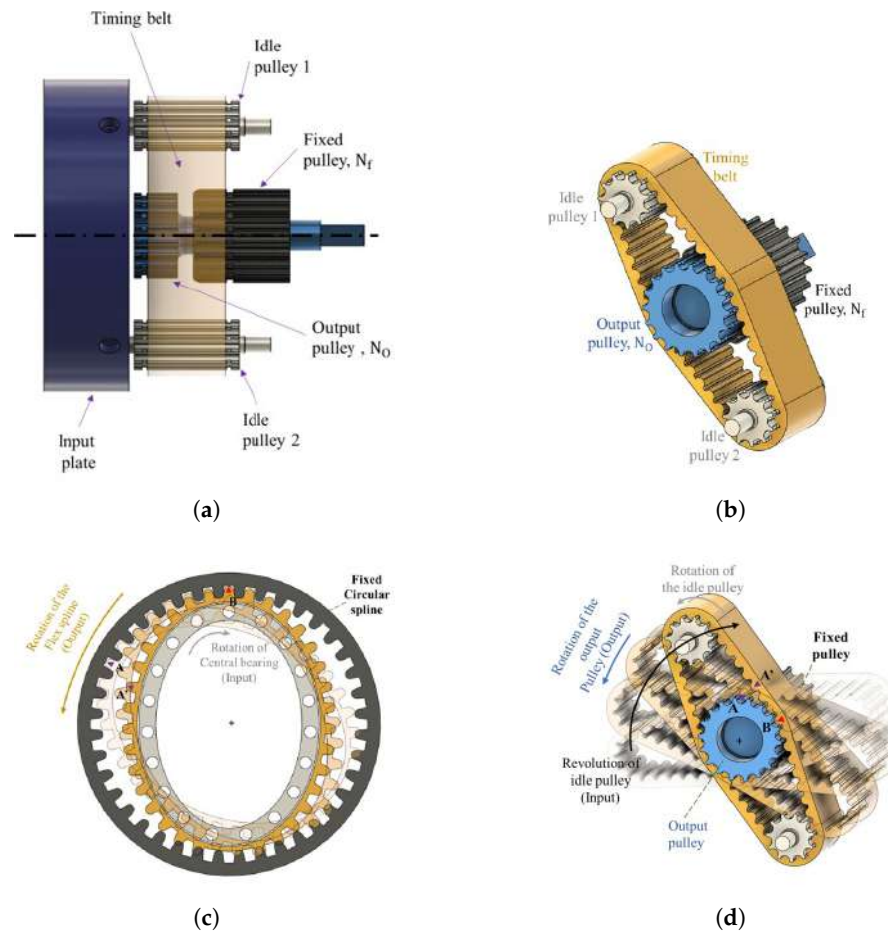


Figure 1. Design concept and engagement mechanism of the belt tooth with the central pulleys (actuation principle is adapted from ref. [38]). Here, (a) illustrates the side view of the key components in the RM-Act 2.0; (b) presents the timing belt and idler pulley arrangement in isometric view; (c) depicts the tooth engagement concept and flex spline motion in a standard harmonic drive; and (d) shows the operating principle of the timing belt mechanism in RM-Act 2.0.

The FP restricts the belt's free motion, causing the engagement points to shift as the belt deforms under the influence of the IPs (Figure 1b). This constrained deformation drives the OP, producing the output motion with a single-stage speed reduction, analogous to a conventional harmonic gearbox. This configuration eliminates the need for precision manufacturing of the FS and internal gear, thereby substantially reducing production costs.

In the configuration illustrated in Figure 2a, the belt teeth engage directly with the central pulleys. During engagement, the belt teeth align those of the output pulley (OP) with the fixed pulley (FP). For each belt tooth, the OP advances by a linear distance BC along the common pitch line of the pulleys. This distance is defined as $BC = P_f - P_o$, resulting in an angular displacement of $\theta_o - \theta_f$ in the OP. The direction of this angular shift is opposite to the input rotation, where θ_f and θ_o represent the angular pitches (https://www.engineersedge.com/gears/gear_terminology_and_equations_13806.htm, accessed on: 28 August 2025) of the fixed and output pulleys, respectively.

$$\theta_{OP} = -(\theta_o - \theta_f) = -360 \left(\frac{1}{N_o} - \frac{1}{N_f} \right). \quad (3)$$

For a complete rotation of the circular plate, the belt teeth sequentially engage with all N_f teeth of the fixed pulley, causing the output pulley to rotate by $\frac{t \times 360^\circ}{N_o}$ in the opposite direction. This results in a speed reduction ratio of $\frac{t}{N_o}$, analogous to that of a conventional

harmonic reducer. Several possible configurations of the belt arrangement can be realized, as illustrated in Figure 3, depending on the value of t , which represents the difference in the number of teeth—and thus the number of contact points between the belt and the central pulleys.

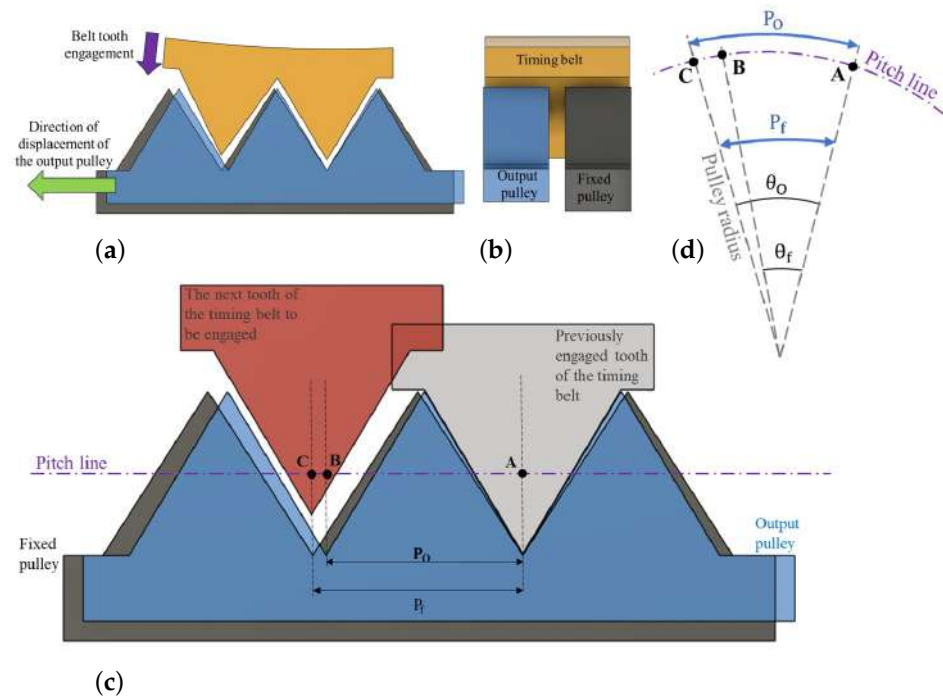


Figure 2. Working principle of tooth engagement process (adapted from ref. [38]). (a) Design concept foot belt-pulley tooth engagement; (b) Motion imparted on the output pulley by the engaging belt; (c) Engagement of the belt tooth with the central pulleys; (d) Diametrical and angular pitch of the pulleys.

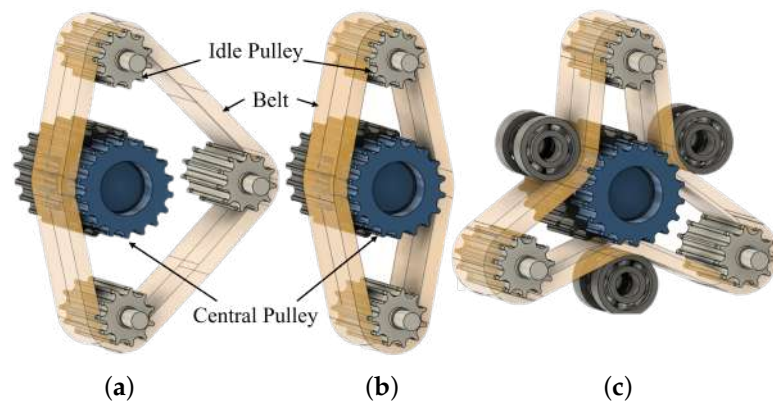


Figure 3. Possible arrangements of idle and central pulleys for different t values: (a) $t = 1$, (b) $t = 2, 4, 6, \dots$, (c) $t = 3, 6, 9, \dots$.

3. RM-Act 2.0—Final Design

This section presents the finalized design of the RM-Act 2.0. The developed model achieves a speed reduction ratio of 9:1 to enable a direct comparison with RM-Act [38]. The components were carefully selected to minimize the actuator's overall size relative to RM-Act [38], while ensuring the use of commercially available parts and reducing machining requirements to enhance torque density and manufacturability.

3.1. CAD Model

Figure 4 illustrates the CAD model of the single-belt RM-Act 2.0 assembly featuring a pair of idler pulleys. To accommodate the bearings and the tensioning mechanism, dedicated input and output plates were designed. The input plate is a cylindrical structure that precisely houses the motor and includes mounting pockets for the idler pulleys, their bearings, and the tensioning system. The output plate, on the other hand, is a hollow circular component that supports the idler pulleys and tensioning assembly while rotating on bearing *D*. Snap rings are used to restrict the axial movement of the belt along the pulleys. The fixed pulley is secured to its complementary profile on the top cover of the actuator. The bottom cover supports the motor and driver module responsible for driving the input plate, whereas the top cover supports the output shaft connected to the output pulley, enabling the transmission of the output motion.

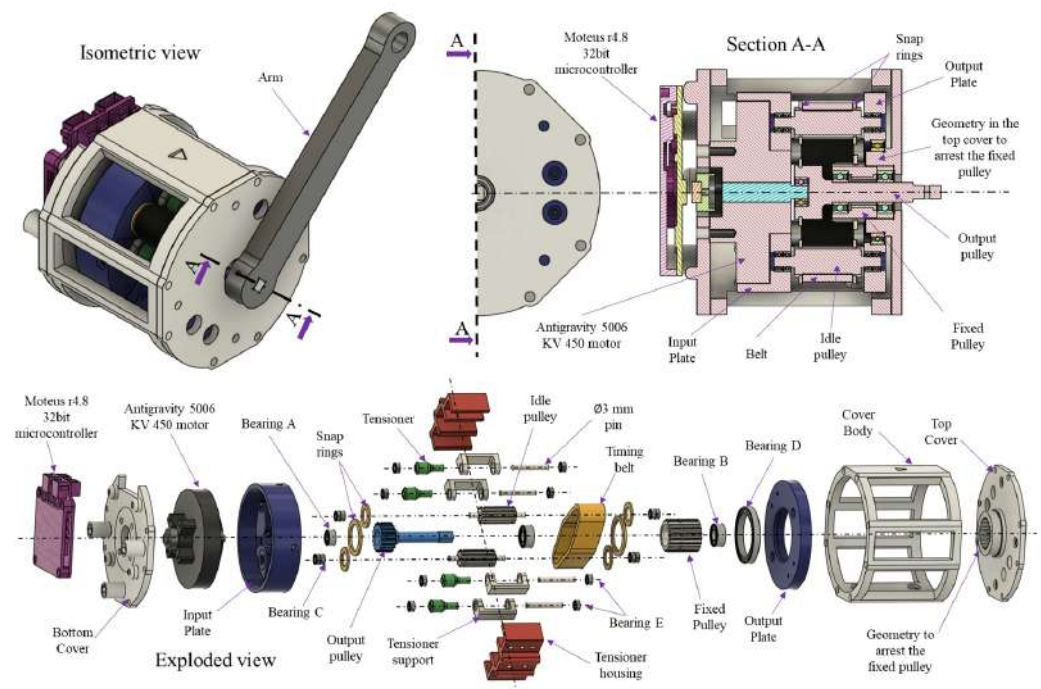


Figure 4. Isometric view of the RM-Act 2.0 assembly (**Top-left**); Sectional view (**Top-right**); Exploded view (**Bottom**).

Bearings with appropriate specifications were selected to meet the functional requirements while minimizing their width, thereby reducing the actuator's overall thickness along its axis. Bearings *A* and *B* facilitate the free rotation of the output pulley relative to both the motor shaft and the fixed pulley. Bearing *C* ensures smooth rotation of the idle plates mounted on the input and output plates. Bearings *E* allow unrestricted rotation of the tensioners, which are mounted on pins within the tensioner support. The belt tensioning system (Figure 5) is specifically designed to minimize slippage of the timing belt and maintain consistent transmission performance.

The tensioner supports are positioned within the tensioner housings, allowing them to slide radially and press the tensioners against the belt. These housings are mounted on the input and output plates. By tightening adjustment screws, the tensioner supports can be moved radially inward to increase the belt tension. The tensioners are designed to maintain uniform tension across the belt segments engaging the output and fixed pulleys.

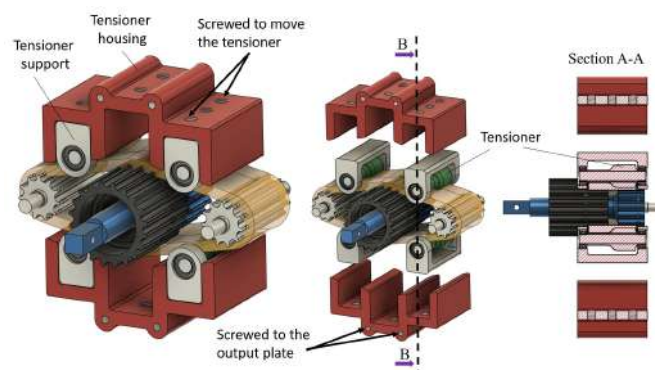


Figure 5. Belt tensioning system of the RM-Act 2.0. Four tensioners are placed to tighten the belt with help of tensioning screws.

3.2. Parts and Material Specification

The RM-Act 2.0 uses an Antigravity 5006 KV 450 motor (sourced from: Ziyang Ave., Nanchang, Jiangxi, China) (<https://store.tmotor.com/product/mn5006-kv450-motor-antigravity-type.html>, accessed on: 28 August 2025) and a Poggi® 120-3MGT-15 timing belt (sourced from: Casa del Cuscinetto S.P.A., Livorno, Italy) (<https://www.poggispa.com/prodotti/trasmissioni-dentate/#1543231689721-30d496d5-522c>, accessed on: 28 August 2025). The idler pulleys, output pulley, and fixed pulley were machined from Poggi GT®3MR bars (11-3MR-80-AL, 18-3MR-125-AL, and 20-3MR-125-AL, respectively) (sourced from: Casa del Cuscinetto S.P.A., Livorno, Italy) (https://www.poggispa.com/wp-content/uploads/2020/01/050_Barre-dentate-e-flange-per-pulegge-dentate.pdf, accessed on: 28 August 2025). Snap rings of sizes 9, 16, and 18 (sourced from: RS Components S.r.l., Milan, Italy) were used to secure the belts on the idle, output, and fixed pulleys, maintaining a clearance of $C_1 = 8.15$ mm between the central and idler pulleys. Bearings A, B, C (and E), and D, shown in Figure 4, were selected as SKF-W-638-4-2Z, SKF-W-628-6-2Z, SKF-W-627-3-2Z, and SKF-W-61705, respectively (sourced from: MISUMI Europa GmbH, Frankfurt am Main, Germany). The components were fastened with Ø3 mm pins and M2/M3 screws, all of which were commercially available.

Additional parts, including the driving plates, tensioners, tensioner supports, and covers, were 3D-printed using ABS plastic with FDM technology. The clearance between the idler pulleys and the actuator cover was set to $C_2 = 6.4$ mm, while the cover itself had a thickness of $z = 3$ mm. A 3D-printed link ($L = 100$ mm, $W = 12.5$ mm, $H = 8$ mm) was mounted on the output shaft to hold loads during testing, as explained in Section 5. The quantities of each component and whether they were obtained commercially or manufactured/modified in-house are summarized in Table 1.

Table 1. List of Components Used in RM-Act 2.0 Assembly.

Component	Specification/Model	Qty.	Source/Manufacturing	Type
Motor	Antigravity 5006 KV 450	1	T-Motor, Jiangxi, China	Commercial
Timing belt	Poggi® 120-3MGT-15	1	Casa del Cuscinetto S.P.A., Livorno, IT	Commercial
Idler pulley	Poggi GT® 11-3MR-80-AL	2	Casa del Cuscinetto S.P.A., Livorno, IT	Commercial + In-house machining
Output pulley	Poggi GT® 18-3MR-125-AL	1	Casa del Cuscinetto S.P.A., Livorno, IT	Commercial + In-house machining
Fixed pulley	Poggi GT® 20-3MR-125-AL	1	Casa del Cuscinetto S.P.A., Livorno, IT	Commercial + In-house machining
Snap rings	Sizes 9, 16, and 18	4,1,1	RS Components S.r.l., Milan, IT	Commercial
Bearing A	SKF W-638-4-2Z	1	MISUMI, Frankfurt am Main, DE	Commercial
Bearing B	SKF W-628-6-2Z	1	MISUMI, Frankfurt am Main, DE	Commercial
Bearing C (and E)	SKF W-627-3-2Z	16	MISUMI, Frankfurt am Main, DE	Commercial
Bearing D	SKF W-61705	1	MISUMI, Frankfurt am Main, DE	Commercial
Fasteners	Ø3 mm pins, M2/M3 screws	Various	Casa del Cuscinetto S.P.A., Livorno, IT	Commercial
tensioners	N/A	1 sets	Aluminum	In-house
supports, covers	N/A	1 each	3D printed using ABS (FDM)	In-house
Moteous microcontroller	r4.8 32-bit	1	Mjbots, Cambridge, MA, USA	Commercial

3.3. Electronics and Control

The Moteus r4.8 32-bit microcontroller was used to drive the three-phase brushless motors, equipped with a built-in magnetic encoder for detecting rotor position and current. As depicted in Figure 6, the Moteus controller achieves high steady-state accuracy by employing the field-oriented control (FOC) method for brushless motor management [41]. The FOC controller operates in two stages: an outer stage featuring a proportional-integral-derivative (PID) controller and an inner stage with a proportional-integral (PI) controller. The outer controller generates the desired voltage and provides torque or current for the quadrature-phase (Q phase) [41]. While the outer stage focuses on torque delivery for the Q phase, the inner stage, operating in current mode, fine-tunes the voltage for the Q torque loop. The motor's control parameters have been detailed in the authors' earlier work [27].

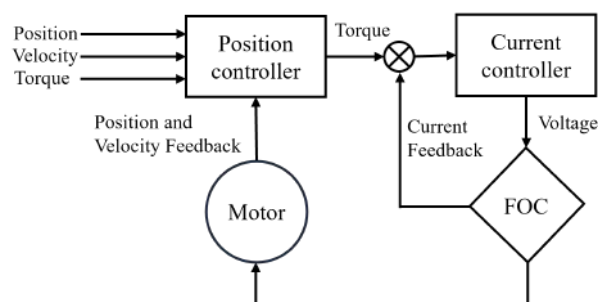


Figure 6. Control scheme of the Moteus controller with a two-stage cascade [27].

Building upon this FOC framework, the higher-level position controller (illustrated in Figure 6) accepts position, velocity, and torque inputs as part of a cascaded control structure integrated within the Moteus controller. The commanded position and velocity are used to compute an acceleration term, which is integrated over time to obtain control velocity and position. These control signals are compared against real-time feedback from the encoder to calculate position and velocity errors, which are then processed through a PID-based control law. The resulting torque command combined with any feedforward torque input is passed to the inner FOC loop for actuation.

Although the target position serves as the main input, the inclusion of velocity and torque signals enables smoother trajectory tracking, improved stability, and enhanced torque precision during dynamic operation, ensuring responsive and high-performance control of the RM-Act 2.0 actuator.

4. Testing and Results

This section details the Python(v3.12.0)-coded tests along with their results. For mounting the RM-Act 2.0 during testing, the bottom and back interfaces (Figure 7) were 3D printed using ABS material.

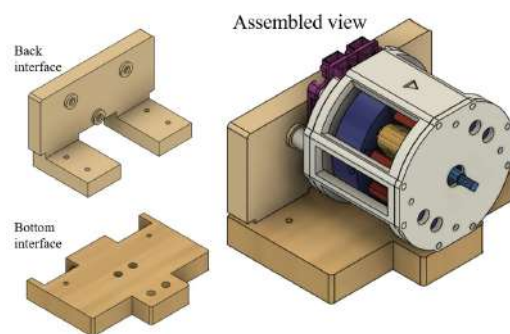
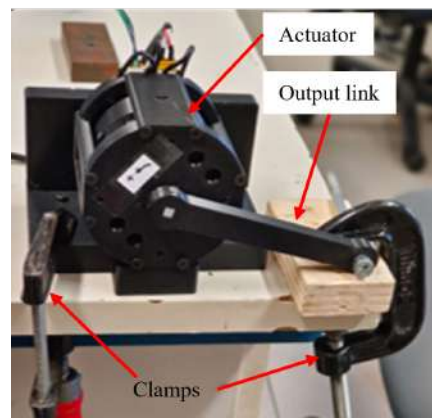


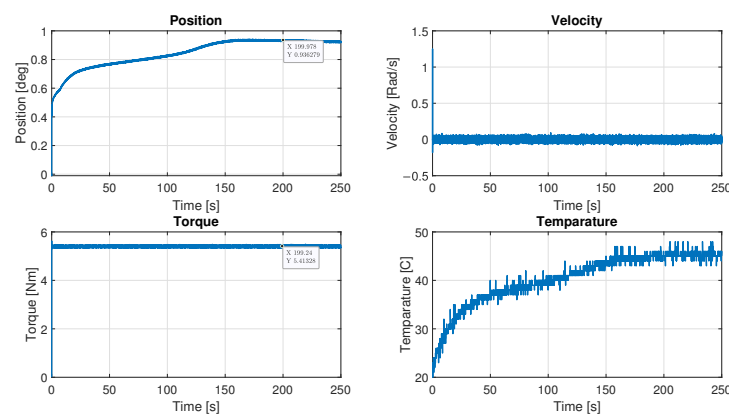
Figure 7. Assembly of RM-Act 2.0 on a mount to prepare a setup for experimental validation. Interfaces to mount the RM-Act 2.0 for tests (left), Assembled view (right).

4.1. Static Tests

The static tests were conducted to evaluate the torque–deflection characteristics of the RM-Act 2.0. During testing, the actuator was firmly mounted on a laboratory table, aligned horizontally along its rotational axis, using the interfaces and clamps shown in Figure 8a. The output arm was fixed while a controlled input torque was applied. Position, velocity, torque, and current were continuously recorded. A linear torque input, starting from 0.1 Nm, was incrementally applied and held until the position stabilized. Given the 9:1 reduction ratio, the output torque was expected to be nine times the input torque.



(a)



(b)

Figure 8. Experimental validation of the actuator with static tests (test procedure is adapted from ref. [38]). (a) Experimental setup for static tests; (b) Results of static tests at the output.

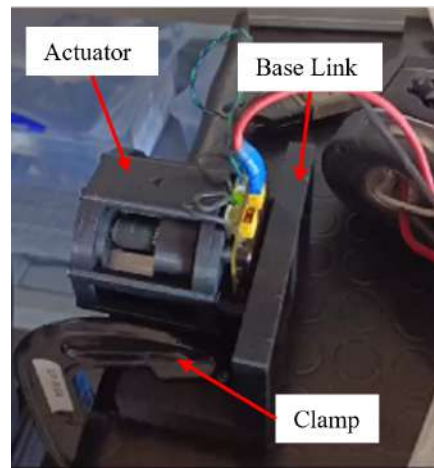
The corresponding output position, velocity, torque, and current for an output torque of 5.41 Nm (from an input torque of 0.6 Nm) are shown in Figure 8b.

The stiffness was determined by analyzing the stabilized position and torque values, which led to an identified stiffness of 360.29 Nm/rad. This stiffness corresponds to a backlash of 0.0159° at 0.1 N·m torque. When the input torque exceeded 0.7 Nm, slippage became apparent. Moreover, for static tests conducted with higher input torques, position stabilization could not be reached, as the temperature of the driver circuit exceeded the manufacturer's specified maximum limit of 60 °C.

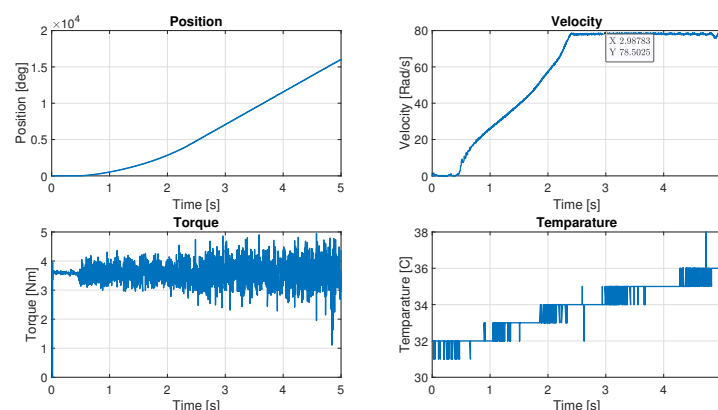
4.2. Dynamic Tests

The dynamic tests were conducted to evaluate the actuator's operational range, focusing on its maximum no-load speed and nominal torque.

For the peak speed test, the actuator was fixed to a platform using C-clamps, maintaining its rotational axis horizontally, as shown in Figure 9a. The output end was left unloaded, and the motor was driven via Python commands to reach its maximum speed with incremental feed-forward torque to overcome friction. Starting from 0.1 Nm, the feed-forward torque was gradually increased. At 0.4 Nm, the actuator reached its peak speed of 78.5 rad/s, as illustrated in Figure 9b, with no further speed increase observed beyond this point.



(a)



(b)

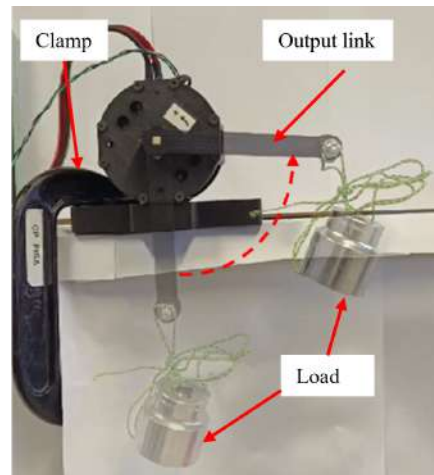
Figure 9. (a) Experimental setup for Maximum speed; (b) Results of Maximum speed tests at the output. The test procedure is adapted from ref. [38].

To determine the nominal torque, the actuator was mounted horizontally on a table. A 3D-printed arm of 0.1 m length was attached to the output, and weights from 0.35 kg to 0.70 kg were applied at the opposite end, as shown in Figure 10a. For each load, the arm was moved from the vertical position to 90°, held for 60 s, and corrected to 100° in code to compensate for deflections and positioning errors. Position, velocity, torque, and temperature were continuously recorded during testing.

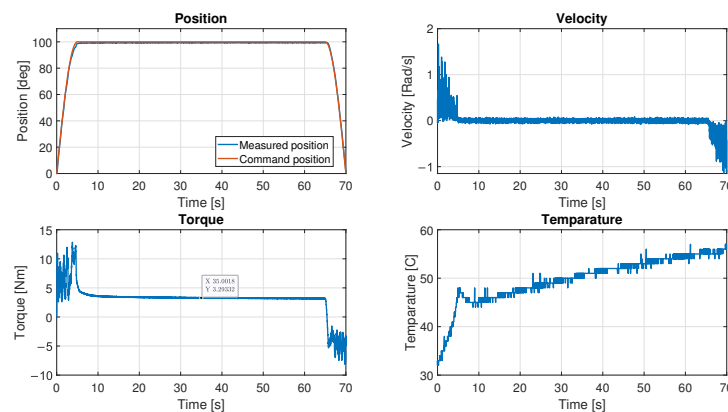
Table 2 summarizes the measured torque values for each load. The theoretical torque, τ_{theo} , was calculated by multiplying the load mass, the acceleration due to gravity, and the arm length. The mean output torque, τ_{avg} , represents the average of the measured torque values over the 60-s holding period. From this, the actuator's nominal torque was determined to be 3.29 Nm, as shown in Figure 10b.

For loads above 0.65 kg, slippage or overheating (temperature exceeding 65 °C) was observed. The deviation between the theoretical and average measured torque can be

attributed to increased internal friction within the actuator, which dissipates part of the motor's input power. Under no-load conditions, the actuator achieved a full 90° motion. The position compensation implemented during the loaded tests was necessary to account for the elastic deformation of the 3D-printed arm under applied loads.



(a)



(b)

Figure 10. (a) Experimental setup for Nominal torque; (b) Results of Nominal torque tests at the output. The test procedure is adapted from ref. [38].

For additional details, the testing videos are available in the Supplementary Materials.

In this study, we did not conduct cyclic loading tests on the actuator. However, the long-term durability and fatigue behavior of the belt can be inferred from a related study in which an actuator with a compound belt gear train, named EM-Act [27], was developed using a similar type of timing belt. The EM-Act was experimentally tested for over one million loading cycles without showing any signs of belt wear or performance degradation. Since RM-Act 2.0 employs belts that are wider and mechanically stronger, comparable or better fatigue performance can be reasonably expected. Nonetheless, we acknowledge that a dedicated long-term durability test for RM-Act 2.0 would further validate this assumption and will be considered in future work.

Table 2. Actuator holding torque test. Loads were placed on an arm connected to the rotation shaft of the actuator. The load were lifted from the vertical axis to the horizontal axis and held for 60 s in the horizontal position. The theoretical torque τ_{theo} and mean average torques τ_{avg} are presented.

Sl. No	Load (kg)	τ_{theo}	τ_{avg}
1	0.350	0.3433	1.3202
2	0.400	0.3924	2.2310
3	0.450	0.4414	1.1047
4	0.500	0.4905	2.1817
5	0.550	0.5395	2.4637
6	0.600	0.5886	2.8606
7	0.650	0.6376	3.2913
8	0.700	0.6867	–

5. Model Identification

This section presents the dynamic testing performed to evaluate the key parameters of the RM-Act 2.0, namely stiffness, inertia, and friction. For model identification, the actuator was mounted on a laboratory table with its rotational axis oriented vertically, as shown in Figure 11a. A known weight of 10 g was attached to the actuator's output end, and oscillations were induced by applying a sinusoidal input torque of 0.23 Nm over a frequency range of 0.005 Hz to 100 Hz. The motor position was continuously monitored throughout the test to obtain the Bode plot of the transfer function's magnitude.

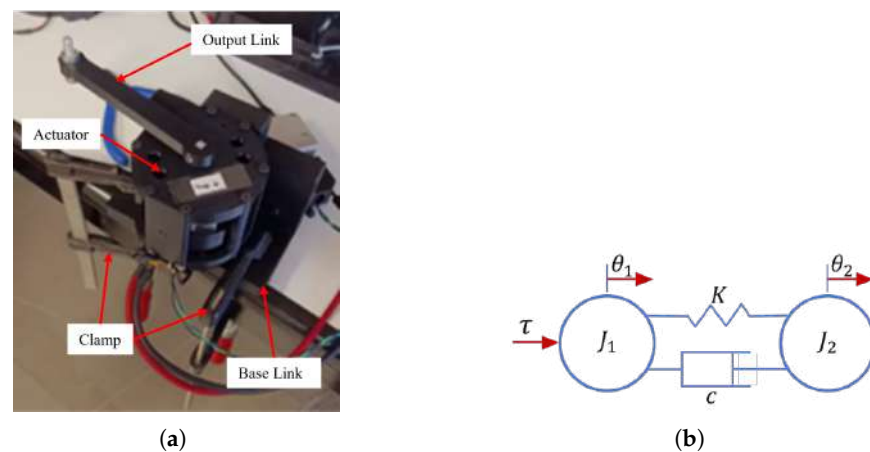


Figure 11. (a) Experimental setup for model identification tests; (b) Actuator stiffness model. The identification procedure is adapted from ref. [38].

The actuator model was represented by the motor inertia (J_1) and link inertia (J_2), coupled through a torsional spring with stiffness K and a damping element characterized by a damping coefficient c , as illustrated in Figure 11b.

For each applied motor torque, τ , the angular positions of both the motor, θ_1 , and the link, θ_2 , were recorded as system outputs. By defining the angular positions and velocities of the two inertias as the system states, the state-space representation of the actuator dynamics is expressed as follows:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{-K}{J_1} & \frac{K}{J_1} & \frac{-c}{J_1} & \frac{c}{J_1} \\ \frac{-K}{J_2} & \frac{K}{J_2} & \frac{-c}{J_2} & \frac{c}{J_2} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \frac{1}{J_1} \\ 0 \end{pmatrix} \tau \quad (4)$$

The motor's angular position and velocity are assigned to x_1 and x_3 , while the angular position and velocity of the link are represented by x_2 and x_4 , respectively. Subsequently,

a transfer function was employed for the frequency domain analysis. This function is characterized by the presence of one integrator, two complex conjugate poles, and a zero,

$$\frac{\theta_1(s)}{\tau(s)} = g \frac{1 + T_1 s}{s \left(1 + s \frac{2d}{w_n} + s^2 \frac{1}{w_n^2} \right)} \quad (5)$$

which was generated from the state space form, where

$$g = \frac{1}{J_1 + J_2}, \quad (6)$$

$$\frac{2d}{w_n} = \frac{c}{K}, \quad (7)$$

and

$$\frac{1}{w_n^2} = \frac{J_1 J_2}{J_1 K + J_2 K}. \quad (8)$$

In Figure 12, the Bode plot of the transfer function's modulus is shown with a fitted curve, which was generated using the MATLAB R2023b curve fitting toolbox (<https://www.mathworks.com/products/curvefitting.html>, accessed on: 28 August 2025). This curve fitting process helped estimate the parameters g , T_1 , d , and w_n . Based on the results from Equations (6)–(8), the values for J_1 , J_2 , K , and c were computed, and the results are presented in Table 3. Notably, the stiffness value obtained from model identification was found to align closely with that derived from the static tests. The final specifications of the RM-Act 2.0 are provided in Table 4. It is important to note that the continuous output power and angular resolution are dependent on the driver's characteristics, while the nominal voltage is influenced by the motor specifications. Furthermore, the actuator's nominal speed was calculated using the values of continuous output power and nominal torque. The maximum torque, which was identified in the static tests, was determined under conditions where the end effector was held stationary, with no slippage or overheating of the components occurring.

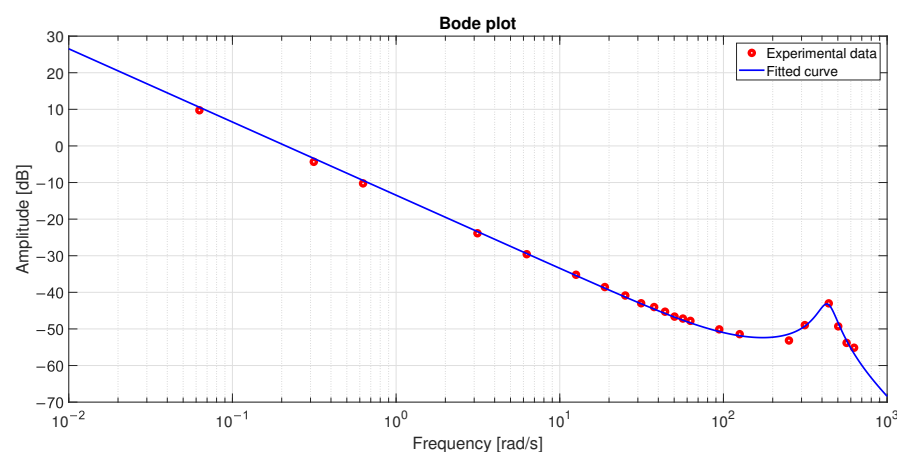


Figure 12. Curve fitting of Bode plot. The calculation procedure is adapted from ref. [38].

Table 3. Experiment results of the parameter identification tests.

Parameter	Symbol	Value
Motor inertia	J_1	$2.1 \times 10^{-3} \text{ kg}\cdot\text{m}^2$
Link inertia	J_2	$1.2 \times 10^{-2} \text{ kg}\cdot\text{m}^2$
Total stiffness	K	360.29 Nm/rad
Friction	c	$3.4 \times 10^{-1} \text{ Nm}\cdot\text{s}^2/\text{rad}$

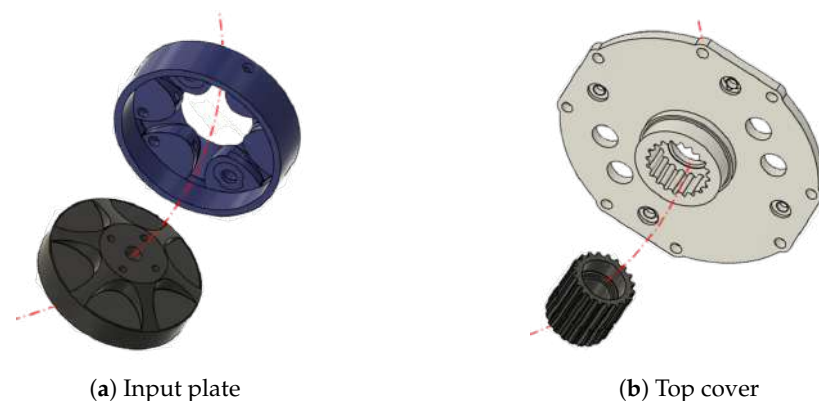
Table 4. Specifications of RM-Act 2.0 in comparison with RM-Act

Parameter	Unit	RM-Act	RM-Act 2.0	Relative Change (%)
Size (Diameter $\times$ Length)	mm	70 $\times$ 95	75 $\times$ 75	−21.05 (Length)
Weight	kg	0.333	0.329	−1.2
Reduction ratio	–	9:1	9:1	0.0
Number of stages	–	1	1	0.0
Total stiffness	Nm/rad	130.4	360.3	+176.4
Continuous output power	W	450	450	0.0
Max. nominal torque (Load)	Nm (kg)	3.36 (0.55)	3.29 (0.65)	−2.1
Max. peak torque	Nm	3.96	5.41	+36.6
Max. speed	rad/s	86.0	78.5	−8.7
Active rotation angle	–	Continuous	Continuous	0.0
Angular resolution	Deg	360/16,384	360/16,384	0.0
Nominal voltage	V	24	24	0.0

6. Quick Comparison Between the RM-Act & RM-Act 2.0 Actuators

Although both RM-Act [38] and RM-Act 2.0 operate on the harmonic principle and employ a timing belt in place of a flexspline, they differ substantially in their development objectives, design methodology, and component configuration. While [38] was conceived to introduce a novel concept and achieve the optimal gear ratio within a predefined volume, RM-Act 2.0 emphasizes enhancing torque density at a fixed reduction ratio by effectively utilizing dead volume and mitigating slippage.

In contrast to [38], the actuator presented here employs a single belt for both central pulleys, which contributes to a reduction in overall actuator length. To further optimize spatial efficiency, the input plate is designed in a cup-shaped form that envelopes the motor surface (Figure 13a). Additionally, the output pulley has been redesigned to accommodate the bearing within its structure, aligning it with the motor shaft. To minimize the use of fasteners and reduce the total number of components, the stop plate used in [38] has been replaced with a complementary geometry integrated into the fixed pulley for secure attachment. The single-belt configuration also reduces the number of snap rings, further decreasing the required assembly space. Thus the total size of the actuator reduces, which can be observed in Figure 14.

**Figure 13.** Modifications for reduced volume. Input plate and Top cover of the actuator were modified.

This configuration helps minimize slippage, leading to higher peak torque and improved load-bearing capacity in RM-Act 2.0 (Table 4). Experimental observations revealed that once a weight was lifted, the actuator could maintain its position even without power, owing to the increased system stiffness. The torque-dense design of RM-Act 2.0 also reduces power losses, resulting in nominal torque values that closely match the theoretical predictions (Figure 15). Overall, RM-Act 2.0 is approximately 20% smaller and 30% stronger than [38].

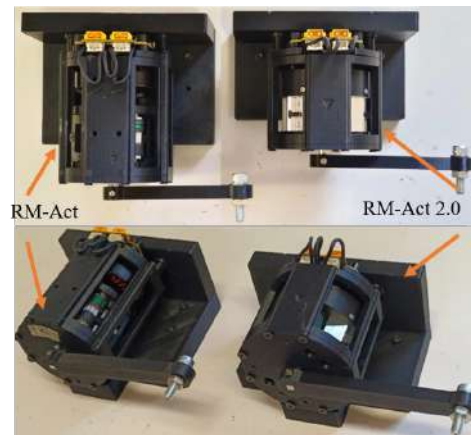


Figure 14. Comparison of the size of RM-Act and RM-Act 2.0.

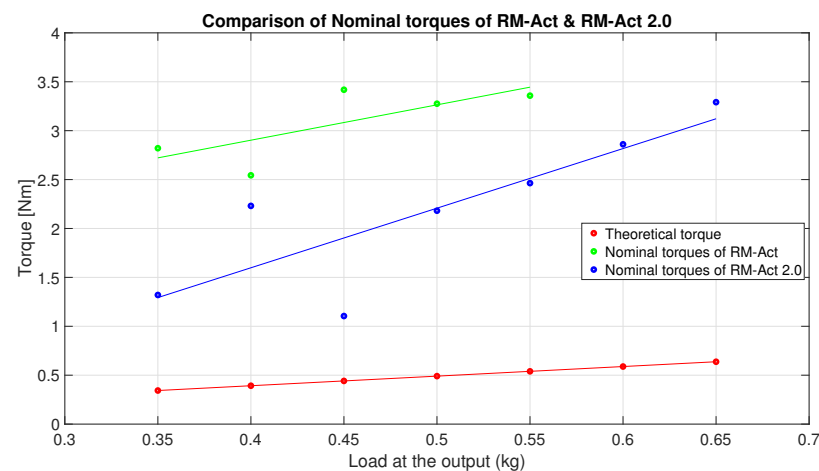


Figure 15. Comparison of the Nominal torques of RM-Act and RM-Act 2.0. w.r.t the Theoretical torque.

7. Conclusions

Harmonic gearboxes, renowned for their exceptional reduction ratios and torque density, continue to represent the state-of-the-art in precision robotics, particularly within collaborative and high-performance applications. This paper presented RM-Act 2.0, a compact and modular harmonic speed reducer designed to achieve a broader range of reduction ratios in a single stage while maximizing torque density. By employing a minimal number of commercially available components, the design effectively minimizes machining requirements and manufacturing costs, thereby enhancing accessibility. Experimental validation confirmed the actuator's robust performance, exhibiting higher peak torque and reduced volume compared to its predecessor, establishing RM-Act 2.0 as a more compact and powerful actuation solution.

Future work will focus on advancing both the mechanical and control performance of the actuator. Planned directions include idler pulley optimization, friction minimization within the transmission, and dimensional compaction through advanced fabrication techniques such as high-resolution 3D printing for improved strength or injection molding for lightweight shell components. Additionally, the actuator will be integrated into a legged robot's hip joint to evaluate performance under dynamic locomotion tasks. Further efforts will target the enhancement of frequency response bandwidth, control stability margins, and thermal performance during continuous operation, contributing to a more efficient, reliable, and application-ready actuation system.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/act14110538/s1>, Video S1: RM-Act-2.0-manuscript-supplementary.mp4.

Author Contributions: This research was led by R.K.M.G., who conceptualized the idea, developed the methodology, designed and prototyped the actuator, and performed the experimental validation. He also drafted the initial manuscript. L.M. assisted in designing and setting up the experiments. A.R. contributed to the conceptualization, and participated in writing, reviewing, and editing the manuscript. F.A. and M.G. provided supervision, reviewed the manuscript, and were responsible for project administration and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

HG	Harmonic Gearboxes
WG	Wave Generator
FS	Flex Spline
CS	Circular Spline
HD	Harmonic Drive
CAD	Computer Aided Design
3D	Three Dimensional
FDM	Fused Deposition Modeling
DOF	Degree of Freedom

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