A NOVEL LINEAR ELECTROMAGNETIC ACTUATOR WITH COMBINED LINEAR AND RECIPROCATING MOTION FOR MECHATRONIC SYSTEMS

Iroda Narimanova
PhD Student,
Department of Mechatronics and Robotics,
Tashkent State Technical University named after Islam Karimov,
Tashkent, Uzbekistan.
Email: iroda3177565@gmail.com
Temurbek Rakhimov
PhD, Associate Professor,
Department of Mechatronics and Robotics,
Tashkent State Technical University named after Islam Karimov,
Tashkent, Uzbekistan.
Email: rahimov_timur@bk.ru
Junjie Yuan
PhD
School of Mechanical and Materials Engineering
North China University of Technology
Beijing, China
Email: yuanjj@ncut.edu.cn
https://doi.org/10.5281/zenodo.17726628

ARTICLE INFO

Received: 24th November 2025
Accepted: 25th November 2025
Online: 26th November 2025

KEYWORDS

linear electromagnetic actuator, mechatronics, traction electromagnets, reciprocating motion, magnetic flux, positioning accuracy, automated systems.

ABSTRACT

This work presents a novel linear electromagnetic actuator designed to provide both linear and reciprocating motion within a single compact system. The proposed design addresses the limitations of classical electromagnetic linear drives, which typically exhibit discontinuous motion, high mechanical wear, low dynamic performance, and limited load capacity. The developed actuator integrates two traction electromagnets positioned on both sides of the ferromagnetic armature, a system of four guiding rollers, flexible cables, and a set of controllable electromagnetic and fixing clutches enabling precise control of motion and positioning.

The combination of electromagnetic traction forces and controlled engagement of the clutches ensures continuous, smooth displacement of the working element without interruption for reversal or preparation phases. The governing electromagnetic force is determined by variations in the magnetic conductivity of the air gap and the additional flux leakage between the armature and the housing, which increases the resulting thrust and improves efficiency. The actuator enables independent control of

motion direction, step length, and fixation, which significantly expands its functional capabilities.

Comparative analysis with known solutions demonstrates that the proposed design offers substantial improvements in accuracy, adaptability, and operational reliability. The ability to generate linear and reciprocating movements simultaneously allows the replacement of multiple actuators in robotic and automated systems, reducing structural complexity and overall mass. Due to its versatility, the device can be effectively applied in conveyors, industrial robots, CNC modules, and high-precision mechatronic systems.

Introduction. Electromagnetic linear actuators play a key role in modern mechatronic systems, robotic mechanisms, automated production lines, and high-precision positioning equipment. Traditional linear electromagnetic drives, despite their wide application, often suffer from structural complexity, intermittent motion cycles, considerable energy consumption, and limited adaptability to variable operating conditions. These limitations significantly reduce the reliability and overall efficiency of systems in which such actuators are integrated.

Classical designs rely on mechanical transmission elements, sliding components, and sequential activation of electromagnets, resulting in discontinuous displacement of the working organ. A significant portion of the operation cycle is spent on returning the actuator to the initial position, which decreases the effective working speed and increases mechanical wear. Furthermore, many existing devices cannot simultaneously generate linear and reciprocating motion, requiring multiple actuators for tasks involving complex trajectories.

To overcome these challenges, this work proposes a novel linear electromagnetic actuator with an integrated mechanism for generating both continuous linear and reciprocating motion using flexible cables, guiding rollers, and controllable electromagnetic clutches. The design provides precise positioning, high operational smoothness, improved dynamic performance, and adaptability to various load conditions. The actuator structure reduces the number of mechanical components and enhances reliability, enabling its application in robotic systems, CNC mechanisms, transportation modules, and automated industrial equipment.

The novelty of the proposed solution lies in the combination of traction electromagnets, a dual-sided armature, and a system of electromagnetic and fixing clutches that provide independent control of displacement direction and fixation. This creates new possibilities for compact multi-functional actuators capable of replacing several single-purpose drives.

Proposed Design

The proposed linear electromagnetic actuator consists of two traction electromagnets positioned on both sides of the ferromagnetic armature, a system of four guiding rollers, flexible cables, electromagnetic clutches, and fixing clutches that enable precise control of displacement. Each traction electromagnet includes a magnetic core, excitation winding, and ferromagnetic armature, which is mounted on rods connected to controllable clutches.

The flexible cable is routed through four guiding rollers located symmetrically on both sides of the actuator housing. When the traction electromagnets are energized, the generated magnetic field pulls the armature toward the corresponding magnet core. By selectively activating the electromagnetic clutches, the motion of the armature is transferred to the cable, creating smooth and controllable linear or reciprocating displacement.

The fixing clutches ensure precise positioning by locking the cable at desired points along its path. This configuration enables continuous motion without the need for mechanical return cycles, significantly improving efficiency and reducing energy losses. In addition, the dual-sided layout allows the actuator to generate motion in both directions with minimal mechanical wear, ensuring long operational life and high reliability in demanding environments.

Applications and Advantages

The multifunctional nature of the proposed actuator makes it suitable for a wide range of industrial and research applications. In robotic systems, the actuator can simultaneously provide linear and reciprocating motion, reducing the number of required drives and simplifying the robot's structure. This improves energy efficiency and decreases the total weight of the mechanism.

In mechatronic modules and CNC equipment, the actuator ensures precise and smooth motion, enabling accurate positioning of working elements during machining, inspection, and automated assembly. The ability to fix the cable at any intermediate position makes the actuator particularly effective for systems requiring high repeatability and fine control of displacement.

Conveyor systems and automated transport modules benefit from the actuator's capability to provide continuous motion with controlled step lengths. The robust design reduces mechanical wear, enhances load capacity, and supports reliable operation in environments with varying dynamic loads.

Key advantages include:

- Capability to produce both linear and reciprocating motion in a single device
- Reduction of mechanical components and friction surfaces
- Higher positioning accuracy due to electromagnetic fixing clutches
- Improved dynamic response and smooth movement
- Universality and adaptability for various industrial systems

Conclusion

The presented linear electromagnetic actuator introduces a novel approach to generating combined linear and reciprocating motion within a compact and energy-efficient structure. The integration of traction electromagnets, flexible cables, guiding rollers, and controllable electromagnetic clutches provides precise and continuous displacement control while significantly reducing system complexity. Comparative analysis with existing designs demonstrates that the proposed solution offers substantial improvements in motion accuracy, operational smoothness, and adaptability.

Due to its multifunctional capabilities and high reliability, the actuator can serve as a universal drive mechanism in robotics, mechatronics, CNC technology, and automated production systems. By reducing the number of required actuators and simplifying the

mechanical structure, the proposed design enhances efficiency, lowers maintenance costs, and expands the functional possibilities of modern electromechanical systems.

References:

1.Boldea, I., & Nasar, S. A. Linear Electric Actuators and Generators. Cambridge University Press, 2015.
2.Krishnan, R. Electric Motor Drives: Modeling, Analysis, and Control. Prentice Hall, 2001.
3.Ehsani, M., Rahman, K. M., & Toliyat, H. A. "Design and Control of Electric Motors for Mechatronic Applications." IEEE Transactions on Industrial Electronics, vol. 48, no. 2, 2001, pp. 223–230.
4.Larsson, A., & Bernhardsson, B. "Electromagnetic Actuators in High-Precision Mechatronic Systems." Mechatronics, vol. 24, 2014, pp. 27–36.
5.Tomczuk, B., & Koteras, R. "Modeling and Analysis of Linear Electromagnetic Drives with Variable Magnetic Conductivity." IEEE Transactions on Magnetics, vol. 52, no. 7, 2016, pp. 1–8.
6.Wang, J., Howe, D. "Design Optimization of Linear Permanent-Magnet Machines for Mechatronic Systems." IEEE/ASME Transactions on Mechatronics, vol. 10, no. 3, 2005, pp. 304–313.
7.Gieras, J. F. Linear Induction Drives. Oxford University Press, 2012.
8.Chiriac, H., & Ovari, T. "Magnetic Flux Control in Electromagnetic Actuators." Journal of Magnetism and Magnetic Materials, vol. 320, 2008, pp. 1820–1825.
9.Lee, S., & Kim, H. "Dynamic Modeling and Performance Analysis of Electromagnetic Clutch Systems." IEEE Transactions on Magnetics, vol. 55, no. 6, 2019, pp. 1–9.
10.Zhang, X., & Yuan, J. "Development of Multifunctional Electromagnetic Actuators for Robotic Systems." International Journal of Advanced Robotic Systems, vol. 16, 2019, pp. 1–12.