

A Cylindrical Linear Induction Motor for Vertical Transfer: A Fundamental Consideration on Thrust Characteristics

by

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(Received on May 11, 2020 and accepted on Jul. 24, 2020)

Abstract

In a conventional elevator, the vibration and twisting of the cable become a serious problem when the cable is very long. Therefore, an elevator using a method that omits the counterweight and is moved by an actuator on a single cable with both ends fixed was considered. However, contact between the actuator and the cable decreases the efficiency and damages the cable owing to the inclusion of foreign matter. Therefore, this paper proposes a vertical transportation system which moves above a long and uniform conductor cable without contact by using a cylindrical linear induction motor (LIM) as the actuator. A cylindrical LIM above the reaction plate, which is a cylindrical shell-shaped conductor, has an advantage that the magnetic force acts on the reaction plate uniformly. This is expected to suppress the vibration in the gap direction. However, a conventional LIM drives the mover in the horizontal direction, and system design guidelines for a device that can directly exert thrust in the vertical direction have yet to be established. Therefore, we constructed a model for analyzing the cylindrical LIM and performed electromagnetic field analyses by the finite element method. The thickness of the reaction plate was varied in the analyses and the effect on the generated thrust was investigated. From the analysis results, the optimum thickness of the cable was determined by obtaining the range of the magnetic flux density acting on the cable.

Keywords: Cylindrical linear induction motor, Electromagnetic field analysis, Actuator, Elevation

1. Introduction

In recent years, many large structures such as high-rise buildings have been constructed. In such a large building, a device such as an elevator is used when carrying a person or a luggage. In general, in a conventional elevator, a cargo area carrying a person or luggage, and a counterweight having substantially the same weight as that of the cargo, are connected by a wire, and the cargo operated by a cable moves up and down¹⁾. However, if building heights increase in the future, the cable will become extremely long, and thus the vibrations and twisting of the cable will become a serious problem^{2, 3)}. Therefore, some researchers have proposed an elevator using a method that omits the counterweight and

moves by an actuator on a single cable with both ends fixed, as shown in Fig. 1. The general actuator for such the elevator

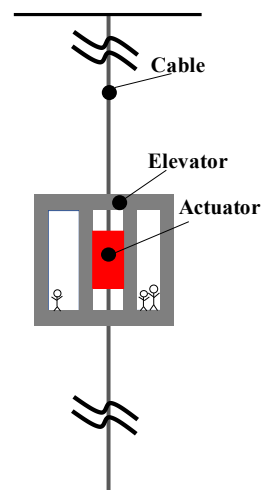


Fig. 1 Schematic diagram of an elevator that omits the counterweight and moves on a single cable.

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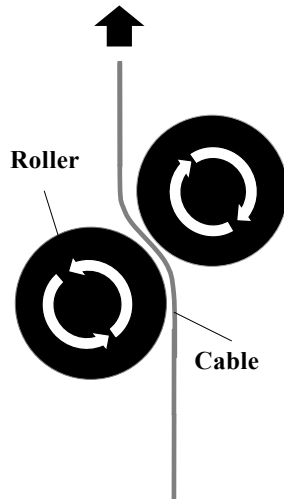


Fig. 2 Conventional method to generate a frictional force for elevation.

has rollers or tires that are driven by an electrical motor and generates a frictional force by contact between the cable and the pulley or tire, as shown in Fig. 2⁴⁻⁶⁾. However, the elevation device requires a frictional force that exceeds the weight of the lifted object. To generate a highly frictional force, some method is considered. One is an increase in the friction coefficient by some surface treatment to the cable or pulley. The other is an increase in the force in the contact surface direction. Conversely, these methods decrease the efficiency and damages the cable owing to the inclusion of foreign matter. The maintenance of the devices and a reduction of the number of replacements are considered to be major issues in the vertical transportation system on the extremely long cable.

To extend the life of such a device, a device that can move vertically without mechanical contact is required. To realize the device, some researchers proposed to use a linear synchronous motor or a linear switched reluctance motor⁷⁾. Although these linear motors need installation of permanent magnets or uneven surface processing on the extremely long cable, these methods lead to increase the weight and decrease the strength of the cable. A uniform shaped object is superior to the installed cable or the processed cable from the viewpoint of weight and strength. Therefore, a linear induction motor (LIM) that moves above the uniform shaped conductive reaction plate without contact is expected in the vertical transportation system in extremely long cable^{8,9)}. A general LIM which is installed above a plane-shaped reaction plate generates a driven force and a perpendicular force to the driving direction. The perpendicular force presses the LIM itself against the reaction plate and changes the gap between the surface of the LIM and the reaction plate. This change causes the vibration of LIM and contacts to the reaction plate. Additionally, it is difficult for the LIM of plane type to

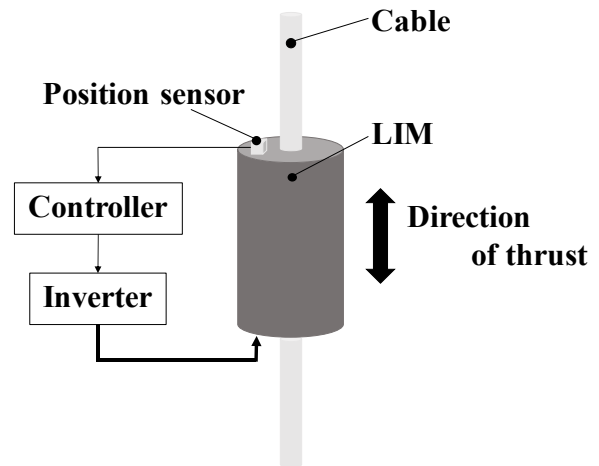


Fig. 3 Schematic illustration of proposed actuator.

maintain the gap between the LIM and the reaction plate against the vibrations caused by various disturbances and torsion.

In contrast, a cylindrical LIM above the reaction plate which is a cylindrical shell-shaped conductor has an advantage that the magnetic force acts on the reaction plate uniformly. This is expected to suppress the vibration in the gap direction. However, a conventional LIM is a system that drives the mover in the horizontal direction, and system design guidelines of a device that can directly exert power in the vertical direction have yet to be established. Therefore, in this paper, our research group proposed a cylindrical LIM that moves vertically above the uniform conductive cable as a reaction plate and investigated the possibility of the proposed LIM for vertical transportation. We constructed an analysis model of the cylindrical LIM and performed electromagnetic field analyses by the finite element method to discuss the vertical transportation performance of the LIM. In addition, assuming that this LIM is used as an actuator that vertical transfer on a super high-rise structure, it is required that the reaction plate be as thin as possible. Therefore, the thickness of the reaction plate was changed in the analyses, the effect on the generated thrust was investigated.

2. Vertical Transfer Actuator Using Cylindrical LIM

Figure 3 shows the proposed actuator using the cylindrical LIM installed above the cable-shaped conductor as a reaction plate. The proposed system used for a position sensor to measure radial and axial displacements. The measured displacements are input to a controller. The controller calculates a control output to maintain the radial gap and axial velocity. The obtained control output is input to a polyphase inverter, and a generated current for driving is input to the LIM. The sinusoidal currents having different phases are input to plural coils in the LIM, and a moving

Table 1 Specifications of the analysis model.

Material	Core	S45C
	Bobbin	Plasstic
	Coil	Cu
	Cable	Cu
LIM	Outer diameter	174 mm
	Inner diameter	100 mm
	Height	264 mm
Cable	Outer diameter	98 mm
	Thickness	1-20 mm
Number of coils		6
Air gap		1 mm

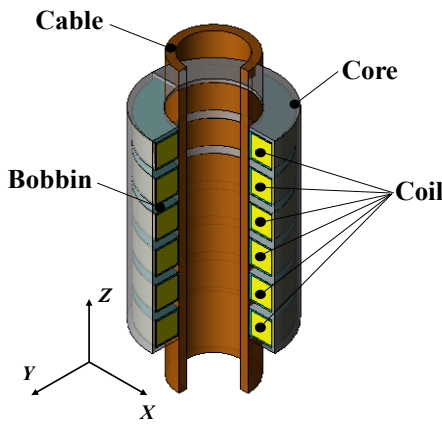


Fig. 4 Analysis model of proposed LIM.

magnetic field is generated. An eddy current is induced in the conductor cable by the generated moving magnetic field. The proposed system uses the Lorentz force generated by the generated eddy current and moving magnetic field to generate thrust.

3. Electromagnetic Field Analysis of the Proposed LIM

3.1 Analysis condition

To evaluate the thrust characteristics and lifting performance of the LIM for vertical movement, an analytical model of the LIM was created and an electromagnetic field analyses were performed. The analysis model is shown in Fig. 4. As shown in Figure 4, the axial direction of the cable was defined as the Z axis and the radial directions of the actuator were defined as the X and Y axes. Table 1 shows the specifications of the proposed analysis model. The LIM which consisted from a core, bobbin, and electrical coils had an outer diameter with 174 mm, an inner diameter with 100 mm, and height with 264 mm. The LIM was made of S45C for the core and plastic for the bobbin. The coils were installed at six locations in the core, and a phase difference was created in the coils using a three-phase AC power source.

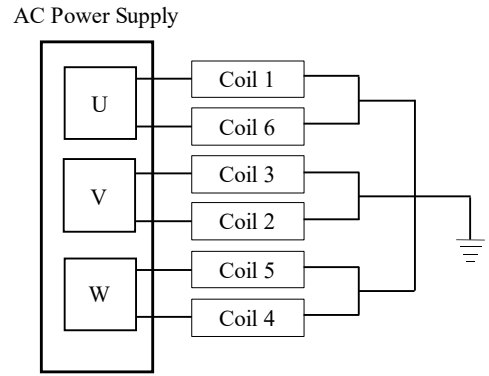


Fig. 5 Circuit diagram of the LIM analysis model.

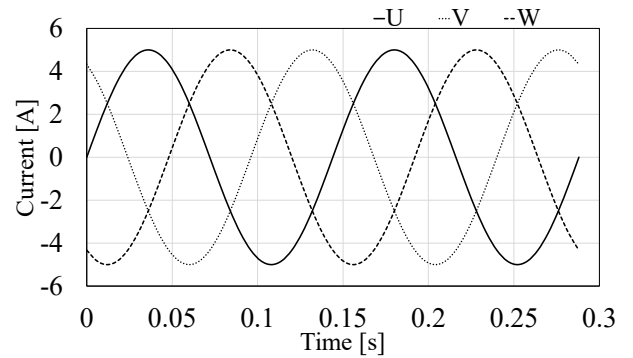


Fig. 6 Time history of input AC power from three-phase inverter.

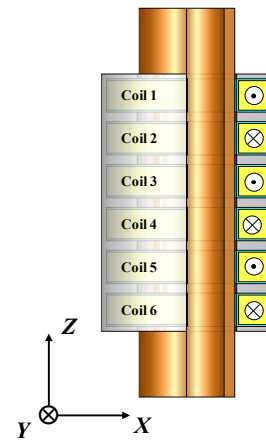


Fig. 7 Analysis model section view.

Figure 5 shows a circuit diagram of the analysis model used to generate a moving magnetic field. In the analysis conditions, the connection method was delta connection. The AC current which consists of U-V-W phase, as shown in Fig. 6, is applied to each coil. Figure 7 shows the arrangement and inflow direction of the coils. The coil can generate a phase difference of 60 degrees. In this study, the effect of changing the cable shape on the LIM thrust was investigated using electromagnetic field analysis. The materials used in the

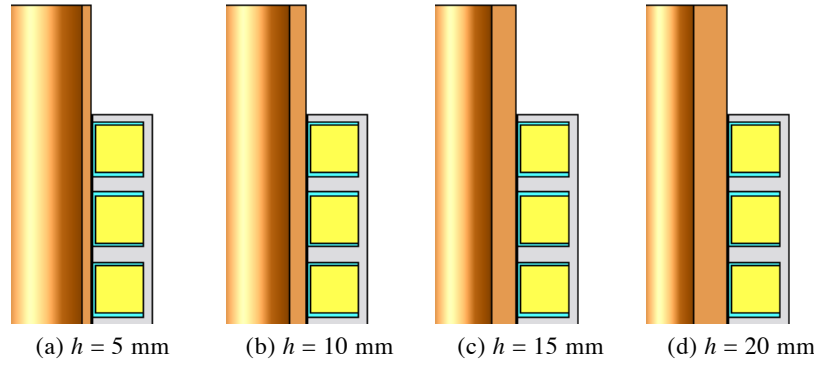


Fig. 8 Analysis model in each cable thickness

cable with outer diameter 98 mm was copper. To examine the effect of the change in the cable thickness on the thrust, the thickness h of the cable was changed from 1 mm to 20 mm under the fixed outer diameter condition. Therefore, the gap between the inner surface of the LIM and the outer surface of the cable was constantly 1 mm in any analysis conditions.

3.2 Finite element analysis model

Figure 8 shows the analytical model when the cable thickness is 5, 10, 15, and 20 mm. The current amplitude was 5 A and the frequency of the AC current was 7 Hz. The analysis time was set to include two cycles of the AC current in 7 Hz. The mass of the analysis model was 17 kg. Therefore, the LIM was required a thrust of about 166.8 N or more to vertical transfer. Transient response analyses were performed under the above conditions. The analyzed electromagnetic forces in the Z axis direction were evaluated as the thrust characteristics.

4. Analysis Result of Thrust Generated by Proposed LIM

From the analysis results obtained by electromagnetic field analyses, Fig. 9 shows the time histories of analyzed thrust generated in the LIM at thicknesses h of the cable with (a) 5 mm, (b) 10 mm, (c) 15 mm, and (d) 20 mm. Analyzed thrusts of all analysis models increased rapidly in the initial term of the analyses. Then, thrusts converged fluctuating to each constant value of thrust. When the thickness of the cable increased, the thrust overshoot largely and needed more time to saturate. It is considered that the inductance of the LIM increased owing to an increase in the thickness of the cable.

Figures 10, 11, and 12 show the analyzed magnetic flux densities, current densities, and Lorentz forces at thicknesses h of 5 mm, 10 mm, 15 mm, and 20 mm. In Fig. 10, although the magnetic flux density near the coils 3 and 6 acts strongly to the inner surface of the cable with thickness h within 10 mm, the flux density on the inner surface decrease when the thickness h was more than 15 mm. It is considered that the

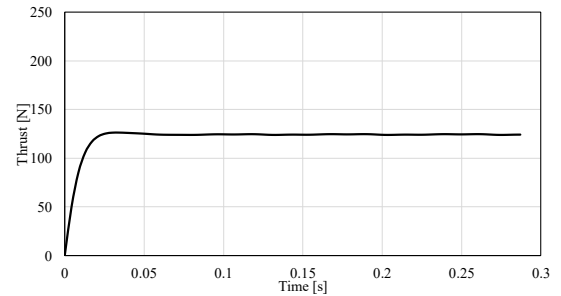
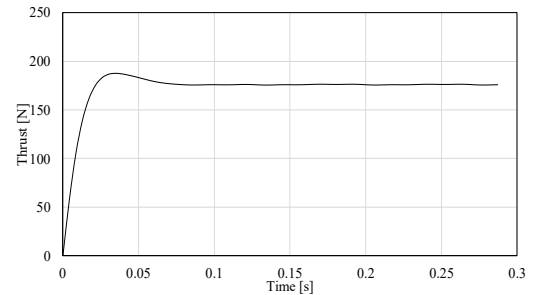
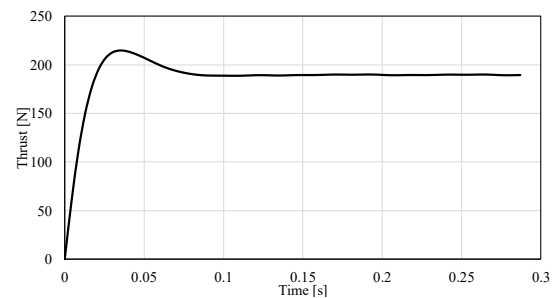
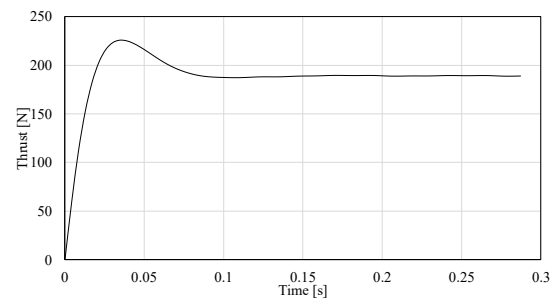
(a) $h = 5$ mm(b) $h = 10$ mm(c) $h = 15$ mm(d) $h = 20$ mm

Fig. 9 Time histories of thrust generated in the LIM.

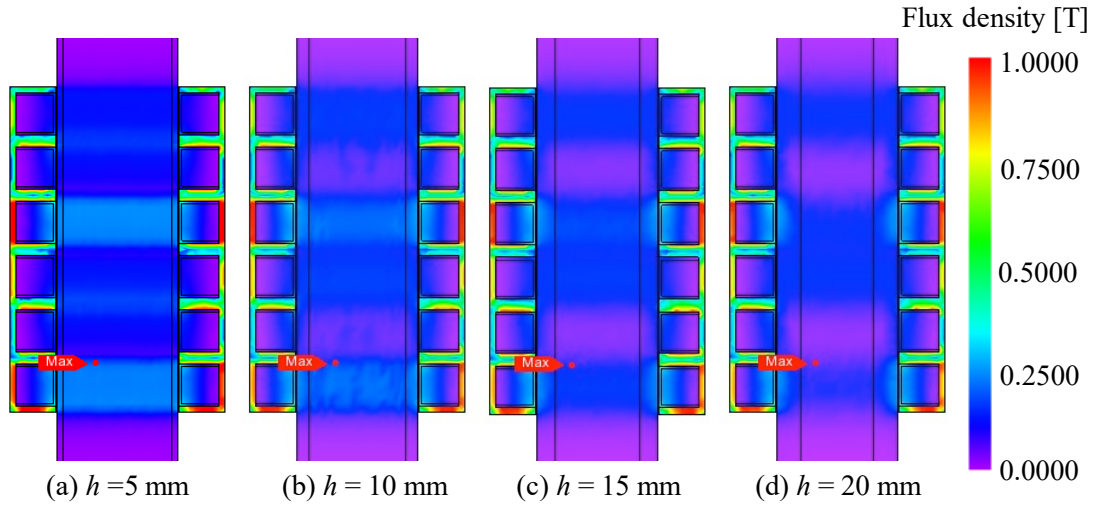


Fig. 10 Contour plot of magnetic flux density.

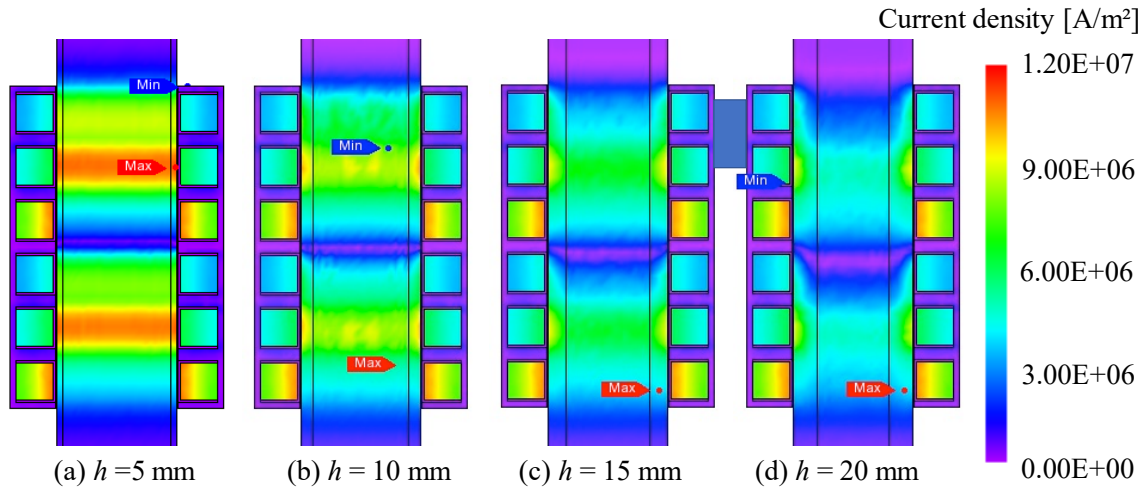


Fig. 11 Contour plot of current density.

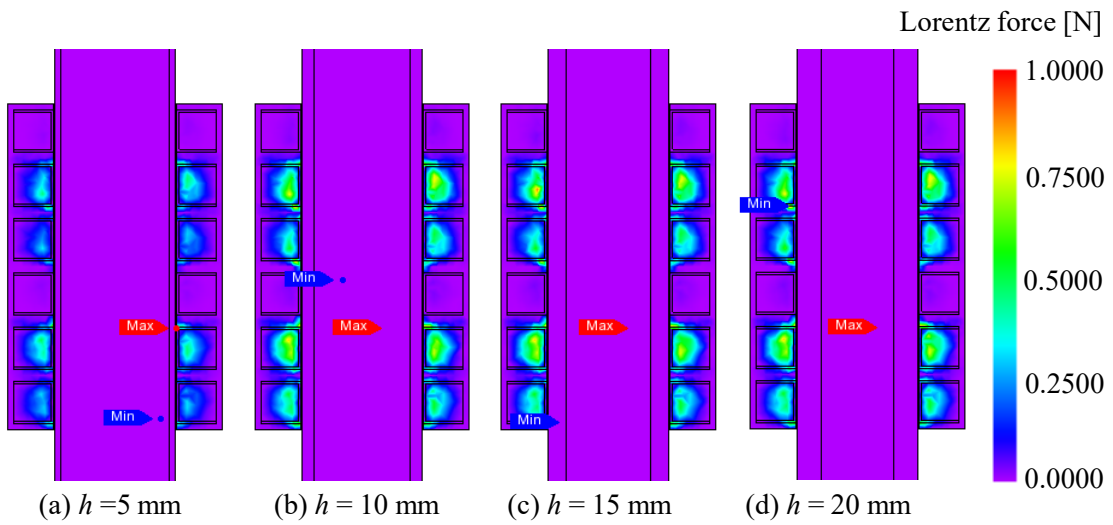


Fig. 12 Contour plot of Lorentz force.

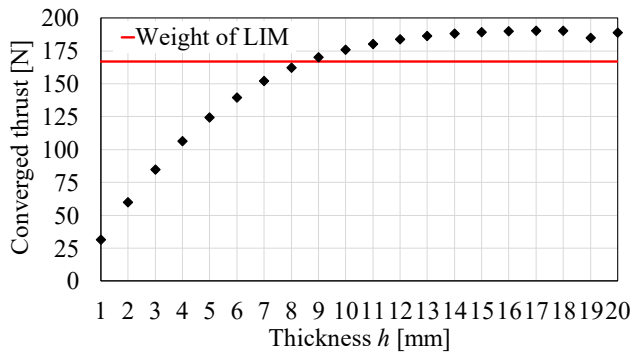


Fig. 13 Relationship between the thickness h and the converged thrust.

cable was too thick for the magnetic flux to through the cable. In Fig. 11, the current density occurred greatly at the coils 3 and 6, and in the cable near the coils 2 and 5. It is considered that the current in the cable was eddy-current which is induced by the moving magnetic field. The current density acting on the cable was reduced by increasing the thickness of the cable. Therefore, Lorentz force as shown in Fig. 12 was greatly generated at the coils 2, 3, 5, and 6 since a Lorentz force was obtained by a cross-product of a magnetic flux and a current. It was confirmed that the current density acting on the cable was reduced by increasing the thickness of the cable, and the thrust increased by increasing the thickness of the cable. Figure 13 shows the relationship between the thickness h and the converged thrust. The converged thrust increased as the cable thickness increased, and saturated in the cases that the cable was thicker than 14 mm. The weight of the LIM is 166.8 N, hence the LIM can generate the thrust to lift itself in the case that the thickness h is thicker than 9 mm.

5. Conclusion

This paper proposed the vertical transportation system which moves above a long and uniform conductor cable without contact by using the cylindrical LIM as the actuator. We constructed an analysis model of the cylindrical LIM and performed electromagnetic field analyses by the finite element method to investigate the possibility of the cylindrical LIM as an actuator for vertical movement. From the analysis results, the thrust tended to increase by increasing the thickness of the cable. However, it was found that the thrust was not increased when the thickness exceeded a certain value since the magnetic flux density acting on the cable decreases with increases in cable thickness. Assuming that it is used as an

actuator that vertical transfer on a super high-rise structure, it is required that the reaction plate be as thin as possible. From these conditions, the optimum thickness of the cable was able to be determined by obtaining the range of the magnetic flux density acting on the cable enough. In the future, we will perform the analysis by changing the material of the cable and adopting a material with high conductivity to improve the thrust characteristics. Furthermore, we will investigate the thrust during running, and a non-contact actuator using a LIM will be realized.

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