Internally-Balanced Magnetic Mechanisms Using a Magnetic Spring for Producing a Large Amplified Clamping Force

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Abstract—To detach a permanent magnet using a control force much smaller than its original attractive force, the internally-balanced magnetic unit (IB Magnet) was invented. It has been applied to magnetic devices such as wall-climbing robots, ceiling-dangling drones, and modular swarm robots. In contrast to its significant reduction rate with regard to the control force, the IB Magnet has two major problems in its nonlinear spring, which serves the purpose of cancelling out the internal force on the magnet. These problems include the complicated design procedure and the trade-off relationship between balancing the precision and the volume of the mechanism. This paper proposes a principle for a new balancing method for the IB Magnet. This method uses a like-pole pair of magnets as a magnetic spring, whose repulsive force should equal the attractive force of an unlike-pole pair. To verify the proposed principle, a prototype of the IB Magnet was designed using a magnetic spring and verified through experiments such that its reduction rate is comparable to those of conventional IB Magnets. Moreover, a robotic clamp was developed as an application example that contains the proposed IB Magnets as its internal mechanism.

Keywords: Mechanism Design of Manipulators, Force Control

I. INTRODUCTION

A. Research Background

A permanent magnet is typically more effective for reducing electricity consumption and thus maximizing operation time in comparison to an electromagnet when a robot uses a magnetic force to adhere to ferromagnetic surfaces. However, as its name suggests, the attractive force of a permanent magnet is exerted permanently; therefore, a permanent magnet requires a large control force for it to be detached from the target object. This characteristic enables it to be attached to the target without consuming any power.

There are many ways for detaching a magnet, especially when used for locomotion. These include: applying a control force originally large enough or reduced enough to exceed the attractive force by a powerful actuator [1-3]; inserting a separator between the magnet and the target object to decrease the attractive force gradually [4]; canceling out the magnetic flux of the magnet by using an electromagnet (which is called an electro-permanent magnet) [5]; and disconnecting the magnetic circuit from the target object by switching the yoke [6]. These methods require an actuator with a high torque, a gear box with a high reduction ratio, or a large current input for the electromagnet. Unfortunately, the advantage of the permanent magnet and its ability to conserve energy for sustaining attraction is ruined in these applications.

B. Internally-Balanced Magnetic Unit

To detach a permanent magnet with a control force much smaller than its original attractive force, the internally-balanced magnetic unit (IB Magnet) in Fig. 2 was invented [7] and has been applied to magnetic devices. Some examples include being a magnetic pad for climbing walls, an anchor for ceiling-dangling drones, and a connection unit for modular swarm robots [8-11].

The mechanism is composed of a permanent magnet for attraction held by the control rod, and a nonlinear spring for internal balancing held by the control rod and the mechanism frame. The spring is designed in such a way that it has a force-displacement repulsion characteristic $F_F(x)$ identical, but opposite in sign, to the force-displacement attraction characteristic $F_m(x) = -F_F(x)$ of the magnet. As a result, the sum of these force-displacement characteristics, which is named the internal force $F_{inter}(x) = F_F + F_m$ exerted on the control rod, is determined to be zero. Because the control rod is then at the equilibrium point of force at any displacement $x$ from the target object, ideally zero control force is required for shifting the control rod to attach and detach the magnet. Meanwhile, the whole mechanism is still attracted to the target object by the counterforce exerted on the frame by the spring.

C. Research Purpose

Even though its control force reduction is effective, the IB Magnet has not been applied widely owing to problems in the nonlinear spring. This is due to its complicated design procedure and the trade-off relationship between the precision of the compensation and the volume of the mechanism. This paper proposes a new internal balancing method that solves these difficulties. A prototype model has been developed to prove the proposed principle; in addition, a robotic clamp has been elucidated herein as its application example.
II. METHODS TO ACHIEVE INTERNAL FORCE COMPENSATION

A. Conventional Method

The conventional nonlinear spring is composed of multiple linear springs (leaf springs, for example) as illustrated in Fig. 2. The state transition is controlled by the displacement of the control rod. To trace the force-displacement characteristics of the magnet that is decreased inversely proportional to the square of the distance, the cam on the frame reduces the number of linear springs that exerts the force as the rod gets pulled out further. The spring can be regarded as a mean of storing attraction work as elastic energy, which gets released as repulsion work when the control rod is pulled out to detach the magnet from the target object.

To optimize the nonlinear spring, optimization should be conducted using the following equations. The loss of energy $\Delta E$ from attraction work to elastic energy is calculated by the attraction work via Eq. (1). This integrates the out-of-balance force at each unit of displacement $dx$ from the target surface $x = 0$ to the maximum stroke of the rod, $x = x_{\text{MAX}}$. This optimization minimizes the $\Delta E$ by choosing spring constants $K_n (K_0 = 0)$ at tangent points $X_n \leq x_{n-1}, x_0 = 0$ for the characteristics of the magnet and solves Eq. (2) to find $x_n$. This is the intersection where the tangent lines meet with the spring constants $K_n$ and $K_{n-1}$. The range $(0, x_{n})$ defines the stroke of a single linear spring with a spring constant $k_n$ that is calculated by using Eq. (3) and (4).

$$\begin{align*}
\Delta E &= \int_{0}^{x_{\text{MAX}}} \left( F_m(x) - \sum_{n} k_n x \right) dx \quad (1) \\
X_n &= \frac{K_n X_n - K_{n-1} X_{n-1} + \{F_m(X_n) - F_m(X_{n-1})\}}{K_n - K_{n-1}} \quad (2) \\
k_n &= K_n - K_{n-1} \quad (3) \\
k_n &= \frac{dF_m(x)}{dx} \bigg|_{X_n} = \sum_{n} k_n \quad (4)
\end{align*}$$

The IB Magnet enables a significant reduction rate of the control force; however, its nonlinear spring has a serious problem owing to its complicated design procedure. As shown above, the nonlinear spring is composed of multiple linear springs. This requires an optimization process that cannot be achieved via a hand calculation. As a result, there is difficulty in developing a practical mechanism for this. The design procedure of the spring can be described as follows:

1. Measure the attraction characteristics of the magnet.
2. Define the stroke of the mechanism and the number of linear springs ($n$) to use. The more springs that are used, the higher the balancing precision (smaller $\Delta E$) that will be achieved.
3. Draw a characteristic graph of the spring by placing $n$ tangent lines to the characteristic of the magnet at $x_n$ and calculate their inclination equivalent to $k_n$.
4. Determine the linear springs with spring constants that are close to $k_n$ and measure their free length.
5. Using $k_n$, provide feedback to the graph to determine the starting positions $x_n$ of the springs and calculate the depth $X_n$ of the cam on the frame.

Furthermore, it is difficult to design a nonlinear spring that is both compact and precisely balanced because of the trade-off relationship between the compensation precision and the volume of the mechanism. More kinds of linear springs are required to make the characteristics of the spring smoother. This causes the characteristics of the magnet to have a decreased deviation while making the whole mechanism larger and heavier. Thus, this mechanism becomes unsuitable, since this reduces the control force that needs to be exerted in a robotic wheel, robotic arm, or a drone with small actuators.

B. Proposed Method: Magnetic Spring

To solve the abovementioned problems, a new internal balancing method was designed using a magnetic spring [12-13] as depicted in Fig. 3. This magnetic spring uses properties of a pair of magnets: the repulsive force characteristic of a like-pole pair, which is called a magnetic spring, is identical, but opposite in sign, to the attractive force of an unlike-pole pair. By aligning two pairs of magnets in the same distance, the sum of their force always equals zero for any displacement. The proposed magnetic spring does not have a more complicated design procedure than a conventional spring:

1. Measure the attraction characteristics for a pair of magnets.
2. Define the stroke of the mechanism, which is equal to the maximum displacement of the springs for the magnetic spring.

The proposed IB Magnet using a magnetic spring is innovative since it is composed of identical magnets. However, it significantly simplifies the design of the basic structure while sustaining or even improving the compensation precision. The contactless and point-symmetric features also give the magnetic spring an advantage of endless rotatability of the control rod relative to the frame.
III. EMBODIMENT OF THE PROTOTYPE MODEL

A. Conceptual Design

Based on the proposed principle, a proof-of-concept prototype of the IB Magnet using a magnetic spring is presented in Table I and Fig. 4. Ring magnets were selected so that a tube-like rod and dry bearings can be placed through the holes for lubrication and future expandability. This includes controlling the rod by the side of the attraction magnet, rotating the control rod relative to the frame and/or target surface, and ducting fluids. Their surface to the corresponding surface (its pair magnet or the target object) is shielded by a cover with a thickness of 1 mm to avoid the ferromagnetic sand. The stroke was defined as 7.5 mm, where a material testing machine (Instron, 3343) measured the attractive force between the two magnets. This force was small enough (0.5 N) so that the covered condition was the same as the prototype model.

B. Building the Prototype Model

Fig. 1 displays the embodied proof-of-concept principle prototype of the proposed IB Magnet using a magnetic spring. Even though it is stiff enough for the proof of concept, a 3D-printed acrylic material (Keyence, AR-M2) is used for the entire structure, which includes the rod for the sake of rapid prototyping. Materials with a higher stiffness such as polycarbonate and aluminum can be used in future research.

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Magnet & Type Number: HX-W1212
Outer Diameter: 18 mm
Inner Diameter: 12 mm
Thickness: 3 mm
Weight: 2.9 g
Diameter
Maximum Length: 15.0 mm
Stroke: 7.5 mm
Weight: 44.3 g

Fig. 6 and 7 shows the 5-time average result of the measurements. (a) When the ascending T-shape hook touches the jig that is connected to the frame, the control force suddenly reaches the highest net value of 8.4 N. This is identical to the maximum attractive force of the original magnet. Afterwards, the detached magnets gradually decreases the control force so it matches the weight of the whole mechanism and the jig. (b) When the jig is connected to the control rod, the control force likely increases; however, the highest net value 1.1 N is apparently reduced to 13.0% of the value during frame pulling. The control force then decreases to the total weight with one rising edge when the rod touches the frame at its maximum stroke. The control force reduction ratios of conventional springs are reported to be 11.8% for six kinds of coil springs and 15.4% for a rubber spring [14]. This experiment successfully validated the effectiveness of the proposed magnetic spring and likely reduced the ratio with a simpler structure and an easier design procedure.

The interference between the magnet for attraction and the one for the frame was not strictly considered but was regarded as weak enough since the shortest distance of 20 mm between them results in a magnetic force of less than 2.0 × 10^-3 N, which is 2.3 × 10^-2 % of the maximum attractive force. By magnetically isolating them from each other using magnetic shields, the interference can be effectively eliminated.

IV. FUNDAMENTAL EXPERIMENT

To prove and evaluate the internal force compensation effect of the proposed IB Magnet using a magnetic spring, this study conducted an examination using the material testing machine as illustrated in Fig. 5. The IB Magnet was placed on and attached to a target acrylic plate with the target magnet buried 1 mm deep. The T-shape hook was attached to the machine to pull up the pulling jig connected either to the frame or to the control rod at the rate of 0.5 mm/sec and to the maximum displacement of 15 mm (twice the stroke). Thus, the values of the control force required to detach the IB Magnet by pulling its frame and its control rod were measured.

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V. APPLICATION OF THE PROPOSED IB MAGNET TO A ROBOTIC CLAMPING MECHANISM

A. Application Concept

This investigation proposed the idea of an “equilibrium-floating force-displacement converter.” This is a mechanism that is composed of a spring with a spring characteristic \( F_{s}(x) \) and an “inverse-spring” with a spring characteristic \( F_{As}(x) = -F_{s}(x) \) to balance the internal force \( F_{\text{INTER}}(x) = F_{s}(x) + F_{As}(x) \) exerted on the connection point of these springs. It is capable of adjusting the force exerted on each end of the springs by shifting the equilibrium point with a minimal control force [15]. In other words, the force of a small, lightweight, and minimal actuator can be amplified to a much larger force by inputting a parallel displacement. The IB Magnet can be counted among the force-displacement converters by regarding the attraction magnet and control rod as the inverse-spring and equilibrium point of the force, respectively. \( F_{s}(x) \) is now \( F_{s}(x) \) and \( F_{As}(x) \) becomes \( F_{m}(x) \) in this view. The end of the inverse-spring corresponds to the attractive force exerted on the frame. This is equal to the weight of the ferromagnetic object so the IB Magnet can lift up at that point for the stroke of the rod. During this experiment, it was decided that the IB Magnet needs to be embedded, especially the one using a proposed magnetic spring to make the design simpler. This mechanism requires control by a large force that includes the attraction target inside the mechanism itself.

B. Clamping Mechanism using the IB Magnet

Owing to their response time, operation time, and power consumption, ideal robotic grippers (i.e., actuator-driven clamps or vises) used in industry and disaster rescue operations should switch the reduction state by one degree of freedom. This can be a high-speed state until the finger touches the object to complete the clamping quickly and a high-torque state after the finger touches the object to sustain the clamping position firmly. Conventionally, this state transition has been achieved by using sensors that provide information regarding the existence of the clamping object between the fingers and the regulating current for the actuator driving an active finger. This electronic method, however, requires a certain processing load and a variable power consumption of the robotic system.

To reduce the complexity of the control, spontaneous reduction mechanisms have been proposed that can be driven passively by a linear actuator, such as a screw with a nut, with a constant extra load (ideally as small as possible) at any displacement of the finger caused by the addition of the reduction mechanism [16-18]. As featured in Fig. 8 (a), such mechanisms use mechanical joints, like toggle and clutch, to restrict the further movement of the actuator position by placing them to the dead center when the finger touches the object. The detection of the load or displacement triggers the switch of reduction state of the actuator. However, they used to be not capable of adjusting the clamping force because these switching mechanisms allow only a binary state of clamping: either zero or maximum force. This is troublesome when the robotic system needs to handle heavy and fragile objects without damaging and dropping them.

To solve these problems, this study proposes a clamping mechanism as displayed in Fig. 8 (b). This requires the IB Magnet to clamp a target by the attraction movement between itself when extended as an active finger and the ferromagnetic surface extended as a fixed finger. Since the magnet enlarges its attractive force spontaneously and gradually as it becomes closer to the ferromagnetic surface, the mechanism can exert a clamping force arbitrarily and a continuous value by shifting in and out the control rod of the IB Magnet. This corresponds to the displacement by using one linear actuator without the extra control force. The actuator requires minimal backlash and a large stiffness so that it can control its own displacement precisely, even if the magnet is close to the ferromagnetic surface and the attractive force significantly changes.

The clamping force can be predicted by the compression length of the spring of the IB Magnet after its frame contacts the ferromagnetic surface. Since the springs are fixed to the control rod, which is separated from the frame, the compression length is adjusted independently from the size of the target object and the distance between the fingers. The clamping force changes the thickness of the target object reduction of thickness during clamping. The gripper can still produce enough clamping force by shifting the control rod until the attractive force sufficiently exceeds the elastic force produced by the deformation. This is because the deformation width does not change after the frames of facing the IB Magnets have contacted each other. Since the attractive force is a known function of the displacement, a variable can be measured and controlled by the encoder of the linear actuator. A direct measurement of the attractive force is not required.

![Diagram](attachment:image.png)

Figure 8. Problems of a conventional mechanical clamp and the proposed clamp mechanism using the IB Magnet.
C. **Enlargement of the IB Magnet using a magnetic spring**

The authors created a stronger IB Magnet using a magnetic spring as displayed in Fig. 9 and 10 and Table 2 to embed in the mechanical clamp. The structure and the control rod are composed of 3D-printed polymer (Stratasys, ABS-P430) and non-magnetic steel (SUS304), respectively. The interfering magnetic force between the magnet on the frame for the spring and the magnet for attraction was measured to be $3.4 \times 10^{-3}$ N, which is $1.1 \times 10^{-3}$% of the maximum attractive force. The measurement described in Fig. 12 was conducted under the same condition as Chapter IV. This showed that the magnetic spring is even valid for a larger scale but with a lower compensation precision.

To avoid the sudden and unintended release phenomenon of the control rod that results in the forced separation of the mechanism and the target object, which occasionally happens since the internal force is too balanced to be easily shifted by a small shake or vibration, a lock mechanism was installed in this version as demonstrated in Fig. 11 (d). This ensures not only the complete attraction state, but also the complete detached state of the magnet to and from the target object. A bearing inserted between the rod and the repulsion magnet makes the attraction magnet independent of the rotation.

### TABLE II. **Specifications of the Enlarged Version of the IB Magnet Using a Magnetic Spring.**

| Magnet | Type Number | No.391 |
|--------|-------------|-------|
| Outer Diameter | 54 mm |
| Inner Diameter | 38 mm |
| Thickness | 5 mm |
| Weight | 40.8 g |
| Diameter | 80 mm |
| Maximum Length | 160 mm |
| Stroke | 20 mm |
| Weight | 683.4 g |

VI. **Embodyment and Experiment of the Proposed IB Magnet Clamping Mechanism**

A. **Conceptual Design**

Based on the proposed principle, a hand-powered proof-of-concept prototype of the proposed IB Magnet clamping mechanism was designed as depicted in Fig. 13. The clamping width is fixed to 35 mm, the height of a loadcell (Kyowa Sangyo, LUR-A-2KNSA), for the latter experiment. The mechanism contains the IB Magnet of Fig. 9. The IB Magnet can be shifted upward for more than its stroke to fit to objects that are thicker than the designed clamping width.

B. **Building the Prototype**

Fig. 14 shows the proof-of-concept prototype of the proposed IB Magnet clamping mechanism.
C. Clamping Experiment

To prove and evaluate the spontaneous reduction effect of the proposed IB Magnet clamping mechanism, an examination was conducted using the prototype model as featured in Fig. 15 and the results are presented in Fig. 16. The fixed finger of the bottom is substituted by a plate 4 mm thinner than the magnetic plate and the attraction target of the IB Magnet is raised 5 mm by inserting an aluminum plate. The mechanism thus clamps an target object 1 mm thicker than its minimum inter-finger distance so that the active finger can touch the object properly to exert a clamping force on it.

This experiment occurred as follows: (b) The loadcell was inserted between the parallel fingers, (c) and the initial load on the loadcell exerted by the weight of the active finger was measured to be 12.9 N, which is the gravity bias of the clamping force. (d) The maximum control force 94.9 N (represented as a mass of 9.68 kg) was required to shift the control rod up and down. This was applied on the rod in the fully pulled-out state. The net clamping force without the spontaneous reduction was measured to be 18.5 N. (e) The control rod was shifted down by hand. (f) The net clamping force with the spontaneous reduction by the magnet was measured to be 36.9 N, which is 2.0 times the original clamping force (d). This shows that the experiment successfully validated the effectiveness of the proposed IB Magnet clamping mechanism.

Figure 15. The clamping experiment for evaluating the spontaneous reduction effect of the proposed IB Magnet clamping mechanism.

Figure 16. Results for evaluating the spontaneous reduction effect of the proposed IB Magnet clamping mechanism.

VII. DISCUSSION

The proof-of-concept prototype of the proposed IB Magnet using a magnetic spring shows a measurable compensation imprecisionness that results in a non-zero control force and a larger deviation of the balance at its enlarged state. It is hypothesized that the cause of this phenomenon could be the difference between the shape of the magnetic circuits. As a result, the exerted magnetic force for a like-pole pair of magnets and an unlike-pole pair of magnets are at the range in which the compression length is almost at its maximum. The deviation between the attraction and repulsion characteristics around the origin may have become larger and more apparent as the volume and the magnetic flux became larger. The authors will conduct a static magnetic field analysis to comprehend this while introducing additional internal force adjustment mechanisms. This includes an offset displacement or a constant force for the attraction magnet so the internal force can be set to zero at the origin and acceptably small for the actuator at the other displacement.

The repulsive force of the magnetic spring always exceeds the attractive force between the attraction magnet and the target ferromagnetic object other than the identical magnet used in this mechanism. To reduce the control force, an offset on the distance between magnets for the magnetic spring can be added so that the repulsive force decreases. In that sense, the merit of a magnetic spring for the IB Magnet can be summarized as the coexistence of simplicity and the balancing precision, especially for applications that can embed a magnet inside the attraction target.

VIII. CONCLUSION AND FUTURE PROSPECTS

This study proposes the principle for a new balancing method that uses a magnetic spring to solve the problems of the conventional nonlinear spring used for the IB Magnet. These problems included a complicated design procedure and a trade-off relationship between the volume of the mechanism and the force compensation precision. To verify the proposed principle, a prototype of the IB Magnet using a magnetic spring was developed. An experiment was conducted to show that its reduction rate is comparable to those of conventional IB Magnets while its structure was simpler. The authors then enlarged the proposed IB Magnet to embody a robotic clamp embedding it as an equilibrium-floating force-displacement converter. Its effectiveness as a clamping force amplifier was verified for the spontaneous force reduction effect.

For future studies, the authors are planning to improve the proposed IB Magnet clamping mechanism. By arranging a pair of opposing IB Magnets with inverse magnetization, both fingers will be active and the deviation of the target object from the center of the clamping point will acquire a larger acceptance. In addition, a load-sensitive spring will be needed to compensate the self-weight component on the internal force that differs by the orientation of the mechanism. Furthermore, an adjustment mechanism of the clamping width between the fingers will be active and the deviation of the target object other than the identical magnet becomes useful in a situation where it needs to handle variable objects with a significantly different thickness. This width-adjustment function should be passive and included in the load-sensitive spring so that the active degree of freedom remains as one, a single linear actuator that drives the opposing IB Magnets.

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