FerroVibe: Towards a Modular Tactile Device

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***Abstract*— This paper presents the proof of concept of the modular nature of ferrofluid based tactile device, FerroVibe. The modularity of FerroVibe allows for customization in degrees of freedom, force feedback, and vibrational cues by strategically positioning magnetic actuators around the central assembly containing a neodymium magnet and ferrofluid. Three distinct configurations of FerroVibe are introduced, each offering unique actuation mechanisms and physical characteristics that could be tailored to different application requirements. The paper showcases the proof of concept and details the working principle of each configuration, highlighting the strengths and limitations of each design. Initial comparative analysis is conducted to evaluate the trade-offs in terms of power consumption, speed, size, weight, and feedback fidelity. The results demonstrate that FerroVibe's potential modular architecture provides a flexible and effective solution for a wide range of tactile feedback applications, making it a promising candidate for future advancements in haptic technology.**

I. Introduction

The sense of touch is fundamental to human experience, enabling us to perceive the qualities of objects, such as pressure, texture, and hardness. This sensory input, distributed throughout the body, is essential for daily activities and human interaction with the environment. As virtual reality (VR) and augmented reality (AR) experiences become more prevalent, the research and development of haptic feedback through kinesthetic [1], [2] and tactile devices have gained significant importance.

Tactile feedback has been shown to enhance user immersion and accuracy in both virtual and real environments. This technology is increasingly integrated into everyday devices such as smartphones and high-precision robots [3]. The skin receptors enable humans to discern the properties of objects, from sharpness to the feel of the wind, making touch an essential sense for various crucial applications, such as robotic minimally invasive surgery where precise tactile information is crucial [4].

Several advancements in tactile technology have been made over the past two decades. The "SmartFinger" enhances tactile sensations by providing vibrations limited to the vertical direction of the finger [5]. The Gravity Grabber, a wearable device that simulates weight sensations through fingerpad deformation without adding actual weight to the user's arms or wrists [6]. Subsequent innovations include vibro-tactile gloves [7], small lightweight tactile displays [8], and 3-DoF wearable devices that provide cutaneous force feedback [9].

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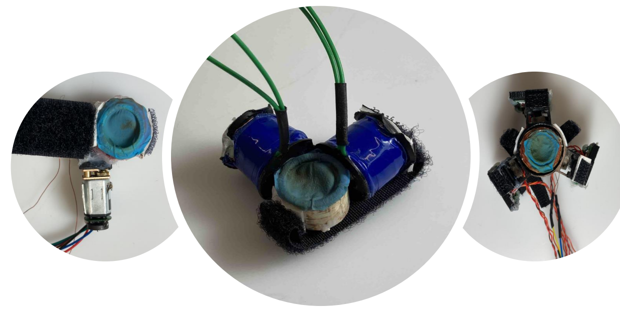


Fig. 1. Prototype designs of the three modular FerroVibe tactile feedback devices.

More recent developments include the 3-RRS wearable fingertip cutaneous device, which uses articulated legs to deliver 3-DoF sensations [10]. The NormalTouch and TextureTouch devices provide detailed tactile feedback through a combination of a tiltable plate and a 4x4 matrix of actuated pins [11]. The HapCube uses magnetic principles to deliver tangential and normal force feedback on the fingertip [12]. FingerTac, a wearable tactile thimble for augmented reality generates vibrotactile stimuli at the sides of the finger, leaving the fingerpad unobstructed for real object interaction [13].

Haptic feedback has become integral to various applications, including assistive technologies for the visually impaired [14], educational tools [15], and sports training devices [16]. These applications leverage tactile feedback to improve navigation, enhance learning, and facilitate non-verbal communication.

In this context, the FerroVibe, a ferrofluid based tactile device, represents a significant advancement. The FerroVibe device uses neodymium magnets, ferrofluid, solenoid and micro motor to provide orientation and vibrational feedback [17]. This paper demonstrates the potential of the FerroVibe as a modular tactile device. The FerroVibe's modular potential allows for the design of tactile cues across various degrees of freedom (DoF), forces, and vibrations by strategically placing magnetic actuators around its main casing, which houses a neodymium magnet and ferrofluid. This adaptability enables the FerroVibe to be tailored to specific tasks, workspace limitations, design preferences, or

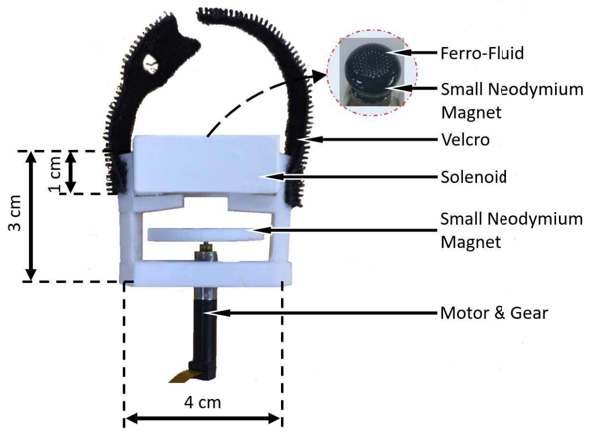


Fig. 2. Prototype of ferrofluid based tactile device presented in [17].

other constraints. Three distinct design implementations of the FerroVibe tactile device are presented (Fig. 1), each with unique actuation and physical properties, while maintaining the same fundamental mechanism, i.e., actuation of the neodymium magnet and ferrofluid using external magnetic fields. This paper provides an initial analysis of the working principle, force and vibrational feedback capabilities of each design, highlighting their respective advantages and limitations. Furthermore, a comparison is included to offer insights into their performance characteristics and suitability for various applications. To the best of the authors' knowledge, no other modular tactile device has been proposed that can be customized to display orientation and vibrational feedback based on the application or requirement at hand.

II. Background and Motivation

The FerroVibe tactile device [17], capable of generating vibrations and conveying information about a real/ virtual object's orientation, Fig. 2, comprises five key modules: a 3D printed casing, a neodymium magnet enclosed in ferrofluid (NMEF), a solenoid, a small external neodymium magnet, and a micro motor with a gearbox and encoder. These components work in unison to create tactile sensation that can cue to the human user feedback from the virtual or real environment.

1. 3D Printed Casing: The casing, fabricated from PLA material using a 3D printer, encloses the neodymium magnet and ferrofluid. The top end of the casing is sealed with nitrile rubber to prevent leakage while ensuring flexibility, impermeability and that the user can feel the NMEF's movements on their fingerpad. The inner walls of the casing are treated with a sealant spray to ensure it is leak-proof.

2. Neodymium Magnet Enclosed in Ferrofluid: A disc-shaped neodymium magnet is placed inside the casing and submerged in ferrofluid. Due to the small height of the disc and its strong magnetic strength, the ferrofluid accumulates equally on both poles of the magnet, thereby causing the NMEF to float centrally within the casing.

3. Solenoid: The solenoid is wound around the casing and produces vibrations and force sensations by varying the frequency and strength of its magnetic field. This magnetic field assists or counteracts the effect of the external magnetic fields to produce desired effects.

4. Small External Neodymium Magnet: Mounted on a 3D printed plate connected to the micro motor shaft, this magnet has an opposite polarity to the NMEF. As the motor rotates, it tends to change the orientation of the NMEF, generating tactile feedback due to the pressure applied by the NMEF on the user's fingerpad.

5. Micro motor with Gearbox and Encoder: Positioned at the bottom of the device, the motor's axis aligns with the casing. The gearbox provides the necessary torque for the motor, enabling the external magnet to overcome other magnetic forces and deliver high-speed excitation of the NMEF.

The FerroVibe operates by exciting the NMEF using external magnetic fields, which allows it to deliver positional information through tilting motions and texture sensations via solenoid-induced vibrations. The behavior of the NMEF is dictated by the position of the external neodymium magnet, where it naturally tends to align with the external magnetic field, as depicted in Fig. 3(a), 3(b). Given that the solenoid generates a magnetic field of greater strength than the external neodymium magnet, when the solenoid is energized with the same polarity as the external magnet and opposite to the NMEF (Fig. 3(c)), the NMEF shifts toward the center of the casing. In this configuration, the magnetic fields of both the NMEF and solenoid align, resulting in no net force applied to the user's fingertip. Conversely, when the solenoid is activated with the opposite polarity to the external neodymium magnet and the same polarity as the NMEF (Fig. 3(d)), the torque exerted by the external magnet is amplified. This increased torque causes the NMEF to further rotate, thereby exerting a greater force on the user's fingertip.

Although the device technically provides 2-DoF in roll and pitch, users can perceive an additional yaw motion due to the continuous rotation of the external magnet. The innovative use of ferrofluid offers several advantages: centering the NMEF inside the casing thereby preventing gravity from affecting it's position, improved heat transfer and cooling of the NMEF, enhanced damping and stability, reduced friction due to its oily base, and prevention of jamming issues.

Despite its advantages, the FerroVibe's design has some limitations, particularly regarding the placement of the motor, which may restrict the user's workspace or complicate interactions in real environments. To address these issues, this paper proposes a modular design approach, demonstrating how different magnetic actuators can be positioned around the FerroVibe based on user requirements, to deliver vibrational and orientation feedback. The modular design of the FerroVibe allows it to adapt to various applications and overcome specific limitations. For instance:

- High Bandwidth Applications: In scenarios where high bandwidth is essential, solenoids can be used instead of motors, making the device suitable for applications such as robotic minimally invasive surgery (RMIS).

- High Force Requirements: When high force is preferred over speed, micro motors become advantageous. This is particularly important for applications involving the sensa-

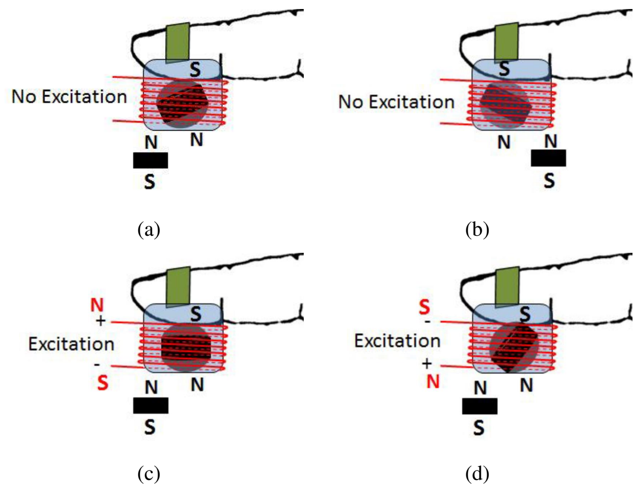


Fig. 3. Working principle of the ferrofluid based tactile device [17]: (a), (b) Orientation of the NMEF as influenced by the position of the external magnet. (c) When the solenoid is excited with the same polarity as the external magnet, the NMEF aligns flat, minimizing exerted force. (d) Excitation of the solenoid with opposite polarity to the external magnet increases the torque on the NMEF, resulting in enhanced force exertion.

tion of squeezing objects, weight cuing, and similar tactile experiences.

This paper presents the design and initial evaluation of three different FerroVibe tactile devices, each with unique actuation and physical properties, but sharing the same underlying mechanism. The design principle, force measurements, advantages, and limitations of each design are compared. By demonstrating the modularity and adaptability of the FerroVibe, this research aims to highlight its potential for a wide range of applications.

III. Design Criteria for Tactile Device

This section outlines the essential aspects and considerations that guide the design and fabrication of the FerroVibe devices. Design criteria can vary based on the task at hand or the application it is intended for. Therefore, there may not be a single device that checks all the boxes.

- Field of Action: The device should interfere as little as possible with the user's natural hand movements.
- Minimized Mechanical Linkages: Reducing the number of mechanical linkages decreases response time and simplifies assembly, enhancing overall device reliability and ease of use.
- Even Mass Distribution: To minimize the inertial effects and enhance comfort, the device's mass should be distributed evenly.
- Degrees-of-Freedom: To deliver a realistic and immersive tactile experience, the device must support multiple degrees of freedom.
- Portability: The device should be portable and accommodate all necessary components within a wearable form factor.
- Power Efficiency: Some actuators like solenoids, while effective, consume significant power. Therefore, careful consideration must be given to the power supply, including battery life and management.
- Tactile Sensation Parameters: Several tactile parameters must be carefully controlled to ensure the device delivers appropriate feedback without causing discomfort or pain. (i) The maximum and minimum force threshold at the fingertip is 3.5 N and 0.8 mN when exerted by a needle if 1.7 mm^2 [18]. (ii) Vibrations up to 1 kHz are perceivable.

IV. Design of Modular FerroVibe

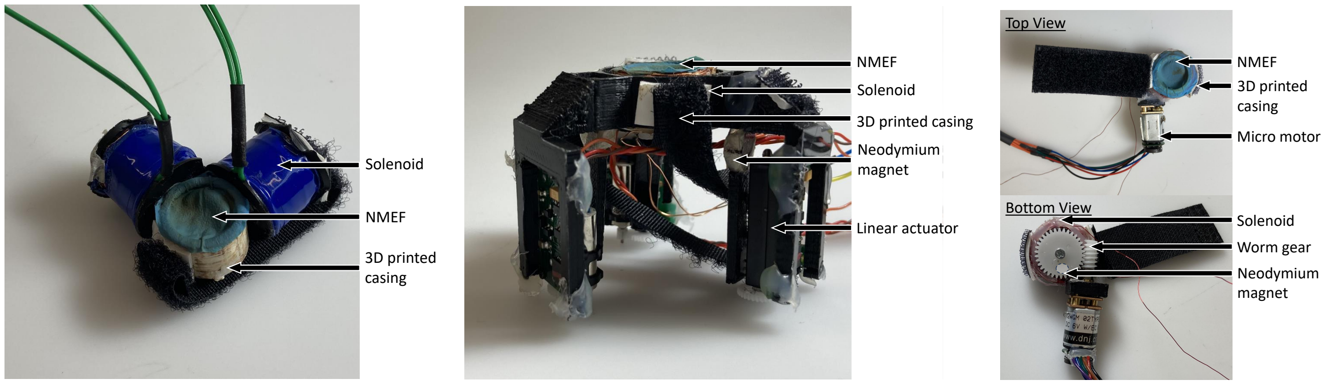
The design principle, hardware used, and actuation principle of the three different designs of the FerroVibe are shown herewith. Please note that all the three designs use identical 3D printed casing. The NMEF and external magnets are disc shaped so that the ferrofluid uniformly distributes on its poles and provides consistent tactile feedback. Safety is a primary concern in the design of the FerroVibe. Research shows that the magnetic fields used in the device, with frequencies below 1 kHz and intensities under 0.15 mT, are safe for human exposure [19]. Studies indicate that magnetic fields of this intensity do not penetrate tissue significantly or cause harm, similar to the safe use of everyday devices like earphones and virtual headsets.

A. Device-1

The first design for the FerroVibe involves the use of two solenoids arranged orthogonally around the 3D printed casing to generate the required magnetic fields, Fig. 4(a). They are used to control the movement of the NMEF by altering their polarity, which can be dynamically adjusted to either attract or repel the NMEF. The solenoids are positioned with a 90° offset to facilitate roll and pitch movements. A roll movement is emulated when one solenoid shifts from an attractive to a repulsive state, while the pitch movement is generated through the same action of the other solenoid. When both solenoids operate simultaneously, the user perceives a yaw movement, as if the magnet is rotating beneath their fingertip. This configuration enables the device to deliver both orientation and vibrational cues concurrently, enhancing the user's tactile experience.

B. Device-2

The design consists of three linear actuators, Spektrum SPMSH 2040L, arranged with a 120º offset relative to one another around the 3D printed casing, Fig. 4(b). Small neodymium magnets, all having the same pole configuration, are attached to the linear actuators, that control vertical motion. This enables an additional vertical movement of the NMEF, which is missing from the other two modular designs. The linear actuators are positioned at this angular offset to create a magnetic equilibrium, ensuring the NMEF remains level when all three motors are at the same height, thereby applying uniform pressure to the user's fingertip. This configuration allows the device to display to roll, pitch, and heave. Additionally, it tricks the user into perceiving a yaw motion. The device can also generate vibrational feedback because of a solenoid wound around the 3D printed casing.



(a) (b) (c)

Fig. 4. Prototypes of the three FerroVibe devices, illustrating key components, and differences in design and actuation mechanisms: (a) Device-1. (b) Device-2. (c) Device-3.

C. Device-3

This design explores the drawback of [17]. Here the micro motor is connected to the side of the device, rather than extending from the bottom. The motor shaft is connected to the worm and an external neodymium magnet is attached to the worm wheel, Fig. 4(c) The polarity of the magnets is crucial for understanding the functioning of this device. When the NMEF has its south pole facing downward, the external magnet is positioned with its south pole facing upward, as illustrated in Figure 3.11b. Due to the off-center placement of the external magnet, the NMEF aligns its magnetic field by tilting towards the external magnet. This design is non-backdrivable, meaning that only the motor can induce a motion of the NMEF by rotating the external magnet.

The motor used is RA12WGM, it includes a gearbox and encoder operating at 6V. Although this motor is primarily for performance testing, it provides valuable insights into the functionality of the device.

V. Comparison Analysis

In this section, we present an initial comparison of the three FerroVibe designs, focusing on various parameters, including power consumption, weight, size, degrees of freedom, speed, force feedback, and heating. These parameters are summarized in Table I.

A. Power Consumption

The power consumption values for the three devices are theoretical, calculated based on their maximum operating conditions:

(i) Device-1: 0.3 A at 2.2 V per solenoid (0.66 W), leading to a total of 1.32 W for both the solenoids.

(ii) Device-2: Each linear actuator consumes 0.15 A at 4.2 V (0.63 W), totaling to 1.89 W for three of them. Additionally, the solenoid consumes 0.3 A at 0.7 V (0.21 W), leading to a total of 2.1 W.

(iii) Device-3: The micro motor consumes 0.2 A at 6 V (1.2 W) and the solenoid consumes 0.3 A at 2.2 V (0.66 W), leading to a total of 1.86 W.

B. Weight and Size

(i) Device-1: This device is the heaviest and weighs 42.2 g due to the dual solenoid configuration but is not the largest in terms of physical dimensions.

(ii) Device-2: This is the largest device, accommodating three linear actuators and a solenoid, but it is the second lightest in weight, 29.7 g.

(iii) Device-3: This design is both the lightest, at 25.9 g and the smallest, optimizing for minimal footprint and portability.

C. Degrees of Freedom

(i) Device-1: Provides 2.5 DoF, with limited mechanical linkages ensuring a high response time and smooth tactile sensation.

(ii) Device-2: Offers an additional DoF, allowing heave alongside roll and pitch feedback to the user's fingerpad, thereby enhancing the realism of tactile feedback.

(iii) Device-3: This model also provides a 2.5 DoF.

D. Reaction Speed

(i) Device-1: Features the highest reaction speed due to the absence of mechanical linkages, leading to quick response times and smooth feedback.

(ii) Device-2: The presence of mechanical linkages reduces the speed, though it could be improved by minimizing motor movement and relying more on the solenoid.

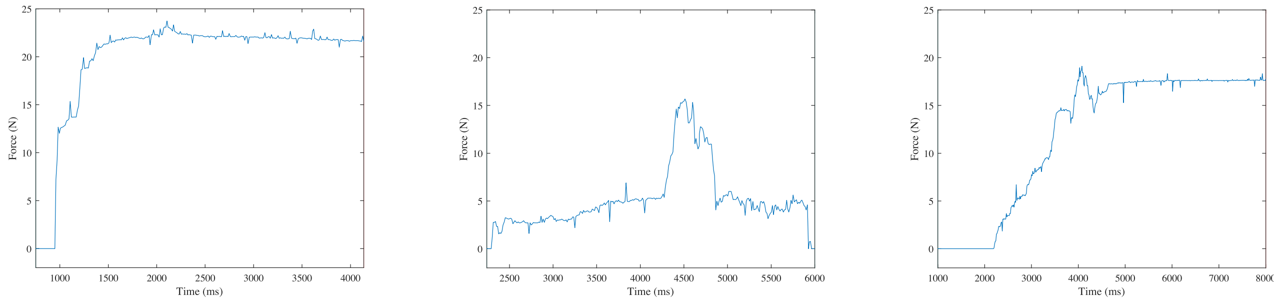
(iii) Device-3: The reaction speed is significantly slower due to the gearbox ratio and worm gear system, making it less responsive, particularly for tactile feedback requiring rapid position changes.

E. Force Feedback

The force delivered by the tactile devices was measured using a Piezoresistive Force sensor (PFS).

(i) Device-1: Provides the strongest force feedback of the three devices, 2.37 N, attributed to the power of the dual solenoid configuration, see Fig. 5(a)

(ii) Device-2: The force feedback of 1.56 N is weaker (Fig. 5(b)) compared to Device-1 but could be enhanced by increasing the solenoid's coil turns.



(a) (b) (c)

Fig. 5. Force response of the three FerroVibe tactile devices: (a) Device-1, (b) Device-2, (c) Device-3.

(iii) Device-3: The force feedback is relatively moderate, 1.84 N, see Fig. 5(c)

F. Heating

(i) Device-1: Tests were carried out whereby it was operated continuously for over five minutes without excessive heating at nominal voltages. Although prolonged use may lead to increased temperatures.

(ii) Device-2: Consumes the most power, leading to potential heating issues, especially if operated continuously. The mechanical linkages also contribute to heat generation.

(iii) Device-3: Prone to rapid heating if the solenoid is continuously energized to maintain the NMEF position, similar to the two solenoids device.

It can be noticed that although the underlying principle of the three FerroVibe device remains the same, their performance aspect is different. While Device-1 has minimized mechanical linkages and higher power efficiency, Device-2 on the other hand, has even mass distribution and more DoF feedback. Device-3 is more portable and ensures better field of action when compared to the other two. Therefore, modularity of the FerroVibe may prove to be effective in having the desired tactile device for the application at hand.

For tele-surgical applications, where precise and instantaneous feedback is paramount, fine-tuning Device-1 could offer surgeons real-time tactile feedback during delicate procedures. This would be particularly beneficial in procedures requiring a nuanced perception of surface orientation, pressure, and texture at the point of contact. In VR environments, the extra DoF provided by Device-2 could enhance immersion by enabling more complex interactions such as grasping, manipulating, and experiencing varying resistance levels in virtual objects. This additional dimension would contribute to the realism and depth of VR experiences. For assistive technologies, particularly devices designed for individuals with visual impairments, Device-3 presents an ideal solution due to its low weight, compact size, and portable design. Integrated into wearable systems such as gloves, this device could reliably convey environmental information, such as proximity to objects or changes in surface texture, providing users with enhanced spatial awareness and improved interaction with their surroundings.

TABLE I
COMPARISON OF THE THREE FERROVIBE DESIGNS

Properties	Device-1	Device-2	Device-3
Size	(35x35x18) mm	(62x51x39) mm	(28x49x17) mm
Weight	42.2 g	29.7 g	25.9 g
DoF	2.5	3.5	2.5
Power	1.32 W	2.1 W	1.86 W
Force	2.37 N	1.56 N	1.84 N

VI. CONCLUSION AND FUTURE WORK

In this paper, we have introduced the proof of concept of the modular nature of FerroVibe, a versatile tactile feedback device designed to enhance haptic interactions through the innovative use of magnetic actuation and ferrofluid. The modularity of the FerroVibe allows for tailored configurations, providing varying degrees of freedom, force feedback, and vibrational cues, which can be customized to meet specific application requirements.

Three distinct configurations of the FerroVibe, Device-1, Device-2 and Device-3, were designed and analyzed, each demonstrating unique capabilities and trade-offs. The initial comparative analysis highlighted the varying strengths and limitations of each design. Device-1 performed better in terms of power consumption, speed and force feedback, however, it was the heaviest and featured 2.5 DoF. Such a device could be suited for tele-surgical applications where the dynamic bandwidth is paramount. Device-2 offered extra DoF force feedback and the inertial effects were minimized due to even mass distribution. It was also the device that consumed the most power and was the largest in size. Device-2 could enhance immersion in VR applications by enabling more complex interactions. Device-3 was the lightest and most compact of the three, but it also featured 2.5 DoF and its reaction speed was the slowest. It could be integrated into wearables, to cue feedback for improved experience and better spatial awareness of the surroundings. It is indicated that while each configuration offers distinct advantages, the underlying modular architecture of FerroVibe provides a robust and flexible platform for developing advanced haptic devices.

Future work will focus on optimizing the designs for specific use cases, modifying the device for the external magnetic actuators to be easily and quickly added or removed from the central assembly, and conducting a thorough user study evaluation with ViESTac [20].

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