The Proactive Desk : A New Force Display System for a Digital Desk Using a 2-DOF Linear Induction Motor

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Abstract

The Proactive Desk is a new digital desk with haptic feedback. The Proactive Desk allows a user to handle both virtual and real objects on a digital desk with a realistic feeling. We proposed it for a co-experience web that would enable people to share the feelings and experiences of other users via the Internet. In the Proactive Desk, two linear induction motors are equipped to generate an omnidirectional translational force on a user's hand or a physical object on the desk without any mechanical link nor wire, thereby preserving the advantages of a digital desk. In this paper, we report applications of the Proactive Desk and the performance of the first trial model.

1. Introduction

The conventional style of Internet communication deals with only digitalized information as it is. Due to the recent IT revolution, we can share and transmit information on a global scale, and we are confronted with communication gaps between generations, cultures and so on. Therefore, a new communication style is necessary to help people to recognize mankind's rich cultural diversity on a global scale, and to enable them to obtain, share and transmit their experiences, feelings and emotions, regardless of their age, locality, occupation, culture or society. To achieve this new communication style, we are developing the technology to form a digital "co-experience web" that will enable people to record and share their experiences [1]. In other words, it will allow us to experience other people vicariously in the same manner as conventional web communication.

The research goal for our group in this project is to explore and develop technological support for the observation and sharing of experiences and emotions through a co-experience web. To provide a basis for this, we study ways to obtain and communicate sensory information and take an integrated approach to the development of technology for recreating information for the five sensory modalities.

Here, we focus on a co-experience web application on a desk, specifically a digital desk that integrates a GUI desktop environment into a real desk. Wellner proposed the concept of a digital desk in 1991 for the first time [2,3]. A typical digital desk enables the user to seamlessly handle the both digital and physical objects on the desk with a common standard. To realize a co-experience web application on a desk, the system also needs to seamlessly react from digital objects toward the user and real objects on a desk. Therefore, we developed a suitable force display for a digital desk system called "the Proactive Desk". The Proactive Desk will be able to sense actions and events on a desk, and will eventually allow us to vicariously experience them.

In this first paper, we report the concept and performance of the first trial Proactive Desk. In the later section, we describe the advantages of a digital desk with force feedback and related research. Then we present the structure and features of the Proactive Desk, and the performance of the trial model.

2. Background and related research

Wellner's "The DigitalDesk" broke though the boundaries between the digitalized GUI desktop and our physical world. Since Wellner's proposition, many systems have been proposed, and they generally have three functions. First, the system projects an image of a PC desktop screen onto a common physical desk as a visual display. Then, the desk simultaneously acts as input device. The user can point to icons with his/her own hands or by using physical tools directly without using a typical indirect input device like a mouse or a trackball. The third function is registration. A digital desk can import a physical object's properties: shape, size, weight, color, number and so on, onto the desktop as digitalized information. By using these functions, a user can seamlessly handle both digital and physical objects on the desk with a common standard. However, the direction of this function is limited, going only from the physical world to the digital desktop. In this research, we add a fourth function, i.e, physical reaction from the digital desktop to the physical world for our co-experience web. Here, a user can handle objects with the feeling of haptic sensation as if handling real objects, and real objects on the desk can react in response to events on the digital desktop.

We will begin by summarizing related works about a digital desk that support the former three functions. In the original digital desk, Wellner used a conventional video projector and CCD camera [2,3]. Leibe proposed the Perspective Workbench [4], which could capture the shape of a physical object on the desk. Adding to the typical digital desk configuration, the Perspective Workbench was additionally equipped with IR illumination lamps and IR filtered CCD cameras to import the object's shadows and digitally construct its shape. The Enhanced Desk and Augmented Desk [5,6] by Koike was also equipped with an IR camera to capture the user's hand action as command input. The user could handle digital objects naturally by using both hands. Smart Skin [7] by Rekimoto was equipped with unique sensor array to detect the user's hands on its table without CCD cameras. The sensor used an electric capacitance meter that was affected by the user's body, and many sensors were embedded under the desk. In his Pick-and-Drop [8], the system emulated the cut & paste function for digital data from a computer to the digital desk in the same manner as physical cutting and pasting. Ishii's group proposed a series of digital desk studies, i.e., meta desk [9], I/O Bulb & Urp [10], Sensetable [11] and Illusion clay [12]. These systems enable the user to handle digital data by using some specialized physical input devices, and were applied to enhance the functions of an urban planning CAD system or optical instrument.

Focusing on the fourth function, "a reaction to the physical world on the digital desk," the desk has to be equipped with a kind of force feedback device. There have only been a few studies in that area because of the difficulty of integrating a force feedback mechanism into a digital desk without spoiling its advantages. As a system that reacts to a user's hand, the desk should have enough power to control both the hand position and reaction force. Therefore, a mechanical link approach is often used. Brederson proposed the Virtual Haptic Workbench [13], which could generate a reaction force by making use of a commercially available mechanical link system, called PHANToM, beside its screen. Ignoreing the advantage of a direct input function of a digital desk, that is to say a system for a conventional GUI desktop, a mouse-like device with a force feedback mechanism could be used. Ramstein's Pantograph [14] employed a 2-DOF parallel link mechanism. Kelley also proposed the MagicMouse [15] using a 2-DOF linear DC motor. These devices could generate enough reaction force for realistic reaction, but these motion range were restricted mechanically within a small area. As another method, the Data Tiles [16] by Rekimoto used a kind of passive force feedback method. In this system, the user combined special functional tiles on the digital desk to achieve some goal, like a data browser. In the motion input tile, there was a small trench as a guide, and the user drove a pen along the trench to input commands certainly and easily.

As reaction for physical objects on a digital desk, a desk simpley controls the position of the objects. The PsyBench [17] by Brave was equipped with an XY stage mechanism under the desk. It had an electromagnet mounted to its end. Putting another small magnet on the bottom of an object, the motion of the XY stage was reflected on the object's movement on the desk. For the user, it would seem like the object moved automatically with the user's action. The Actuated Workbench [18] by Pangaro succeeded the PsyBench. In the Actuated Workbench, the XY stage mechanism was replaced with set of a electromagnetic coils, and they worked as a 2-DOF linear pulse motor. Controlling the degree of magnetic field for each coil, it could manipulate two or more physical objects together on the desk. As another pulse motor approach, Fries proposed the Sawyer motor driven system [19]. Using the motor, it could attain micron-level object motion resolution, however, a moving unit on the desk had to have sets of electromagnets and wires.

For the mechanical link approach, scalability is a critical problem. A sufficently large link system was required to support the entire working area with the size of a desk. Such a huge mechanism on the desk, however, prevented visual projection and spoiled the seamless usability of the digital desk. Moreover, the singular point problem that is peculiar to a complicate mechanical link is unavoidable. On the other hand, the XY stage and linear pulse motor approach could move objects on the desk well, but they could not generate enough reaction force on the user's hand on the desk.

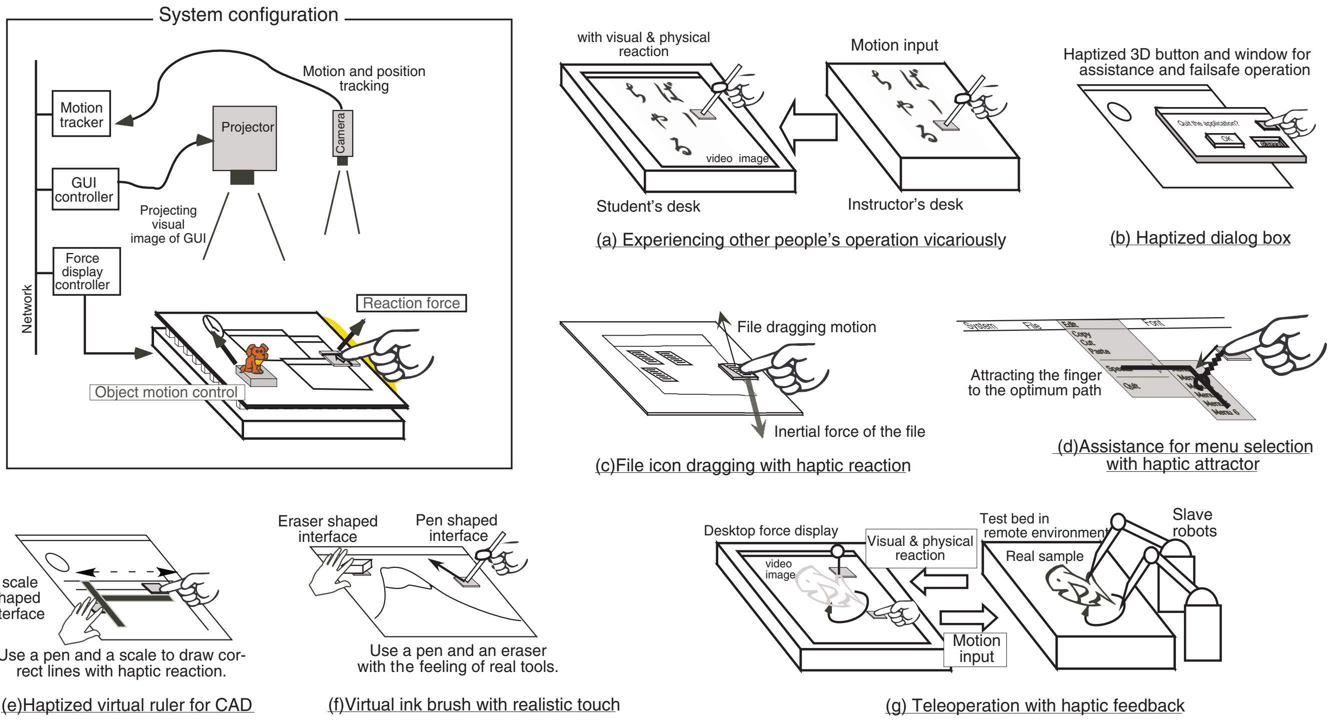
Against this background, we propose the Proactive Desk, which was equipped with built-in linear induction motors to provide an active force feedback to both the user's hand and objects. The main advantage is that the Proactive Desk does not prevent visual projection because the whole mechanism of the motors is built into the desk. Moreover, it is not necessary to attach any wires to the user's hand or to the physical objects.

3. Applications

We will now discuss applications of the digital desk with haptic reaction before giving a technical description of the Proactive Desk.

The Proactive Desk allows a user to handle objects on the desk with a feeling of haptic sensation as if he/she were handling real objects. It can also move physical objects in response to events on the digital desktop. Applying the advantages to our major target, the “co-experience web” project, the digital desk can record the user s operation on the desk digitally, and can allow other persond to relive the experience of the operation. As shown in Figure 1-a, when the trainer draws calligraphy on the desk, the drawing operation can be input. The student can then go over the writing as if his/her hand were being taken by the trainer.

We also propose to apply the force feedback into a di-



(a) Experiencing other people's operation vicariously

(b) Haptized dialog box

(c)File icon dragging with haptic reaction

(d)Assistance for menu selection with haptic attractor

Use a pen and a scale to draw correct lines with haptic reaction.

(e)Haptized virtual ruler for CAD

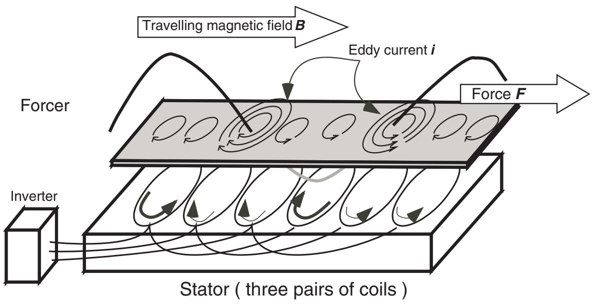
Use a pen and an eraser with the feeling of real tools.

(f)Virtual ink brush with realistic touch

(g) Teleoperation with haptic feedback

Fig. 1. Applications of the Proactive Desk

rect assistance function for the user as expansion of a conventional GUI. When the user has to respond to some alert dialog, the force feedback can raise the physical barriers on critical options for fail-safe operation as shown in Figure 1-b. Here, the user needs to make a conscious action to select the critical one. The system can also present physical information by expanding the visual GUI. For example, the system can represent the size of some files as an inertial force to the user. In other words, the user can feel the size of a dragged file as its weight (Figure 1-c). Next, it is difficult to select a sub menu in some GUI system, because most GUIs require us to move the mouse exactly along a narrow path. Putting a virtual spring between the path and the user's fingertip by using force feedback as shown in Figure 1-d, the user can select sub menus difficult manipulation.



1:Coils generate travelling magnetic field ***B***.
2:Avoiding the field, eddy current ***i*** is induced on the forcer.
3:The current ***i*** and magnetic field ***B*** generate force ***F*** on the forcer using Fleming's left hand rule.

Fig. 2 Principle of operation of the LIM

Applying force feedback to CAD or drawing software as shown in Figure 1-e and f, the user can use haptized virtual or real equipment, such as a virtual T square, a virtual pen, a virtual brush and other items with the feeling of haptic sensation.

Of course the system can also be applied to an interface device for teleoperation (Figure 1-g). Here, the motion of the user's hand and some real instruments on the desk are transmitted to slave robots in a remote place. Simultaneously, a reaction is received by both the user and the instruments as force and position feedback.

In these applications, we should note that the Proactive Desk can offer direct haptic feedback without spoiling the advantages of the digital desk.

4. Linear motor for a digital desk

We built linear induction motors into the digital desk for force feedback in the Proactive Desk. Generally, a linear motor consists of a stator and a forcer, which correspond to the stator and the rotator in a rotary motor. Each one moves straight along the other one and there is essentially no mechanical limitation in its range of movement.

Linear motors can be categorized into four types: the Linear Induction Motor (LIM), the Linear Synchronous Motor (LSM), the Linear Pulse Motor (LPM) and the Linear Direct-current Motor (LDM) corresponding to existing rotary motors. The Actuated Workbench and the Sawyer motor are a kind of LPM. The MagicMouse is a kind of

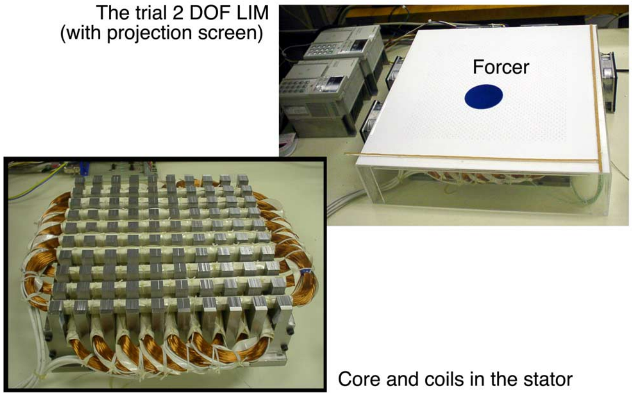


Fig. 3. The first trial Proactive Desk

LDM.

The reason why we employed the LIM is that its moving part, a forcer, is just a conductive material plate. In other words, by putting a small metal plate onto a user's finger or some object, the LIM can control a translational force on them. For the other linear motors, heavy permanent magnets or wired coils need to be attached to the user, which spoils the advantages of the digital desk in a way that is similar to the mechanical link approach.

Let us briefly explain the principle of the LIM. The LIM has the same mechanism as the widely used standard AC three-phase rotary motor. In the stator, three pairs of coil sets are lined up along the moving direction as shown in Figure 2. When a three-phase current is turned on to each coil set, the traveling magnetic field ***B*** is generated along the coils. Avoiding the field, the eddy current ***i*** is induced on the forcer, and the current ***i*** and the magnetic field ***B*** generate the translational force ***F*** on the forcer by Fleming's left hand rule. The LIM is characterized in that it can control the translational force by means of the frequency and current applied to the stator, and the maximum force is generated when the forcer is stopped. Of course there is no active mechanism on the forcer. The force is simply a conductive material. On the other hand, the LIM is inefficient in converting between power and force, and it needs a cooling mechanism.

Ohira proposed a bidirectional LIM [20,21] in 1982. Two sets of coils were placed in orthogonal orientation among the stator core, and each set of coils was driven individually by two AC inverters. Therefore the motor can generate any power of the traveling magnetic field in any direction on the table. He has applied the motor to a branch mechanism of a conveyance system in a factory. We aimed at the advantages of force controllability and a simple wireless forcer, then implemented this to our Proactive Desk.

5. The trial 2-DOF LIM for the Proactive Desk

We made a trial 2-DOF LIM as the most important part of the Proactive Desk, referring Ohira s LIM, and conducted experiments in order to measure the performance of the LIM as a digital desk.

5.1. Design of the trial 2-DOF LIM

We designed the trial 2-DOF LIM by consulting Ohira's bidirectional LIM for the Proactive Desk. Figure 3 shows the trial system. As for the primary iron core that acts as the base part of the stator, non-directional silicon steel plates that were punched out in a comb-shape were stacked in the vertical and cross directions. The core was formed of a typical CPU heat sink, and it had nine x nine slots in which coils were placed. The dimensions of the desk were 285 mm x 285 mm. This was the area in which the desk could generate force. The slots were placed 15 mm apart and the width of each slot was 15 mm. The height of the slot was 60 mm for lower the coils and 30 mm for the upper coils. The forcer should be placed just above the core to obtain maximum effectiveness. However, we placed an acrylic resin board between the core and the forcer for a later mentioned reason. In this configuration, the gap between the core and the forcer was 7 mm.

The primary coil sets consisted of three pairs of a series of two coils, and six coils in all were used in each direction. One coil was turned two hundred times. Two sets of the primary coils were placed inside both the upper and lower slots in orthogonal orientation. In this trial system, the coil pitch was three slots, or 45 mm.

In order to close the magnetic circuit to obtain higher effectiveness, we need to use a nonmagnetic conductive plate stacked onto a magnetic conductive one, such as a pair of aluminum and steel. However, the steel part was also attracted to the stator, and this reluctance force cause a bigger frictional force than translational force. Therefore, the forcer needed to be only a nonmagnetic conductive material plate.

The three pairs of coils are connected to an inverter unit for a standard AC motor using a star connection. We used one inverter unit for each axis. The capacity of each inverter was 2.4 kW. Here, the voltage and current in the coils were managed by the inverter itself, and we could only control the frequency of the AC signal in the coils to obtain the desired translational force on the forcer.

As shown in later experimental results, a few amperes of current are applied to the coils to obtain enough force. Therefore, the user should be kept apart from the coils as much as possible. Moreover, the gap between the core and the forcer should be kept constant to obtain uniform performance everywhere on the desk. Furthermore, as a visual display, a screen is necessary. For these reasons, the stator is covered with an acrylic resin box. A few fans were attached to the side panel for the forced air cooling of the

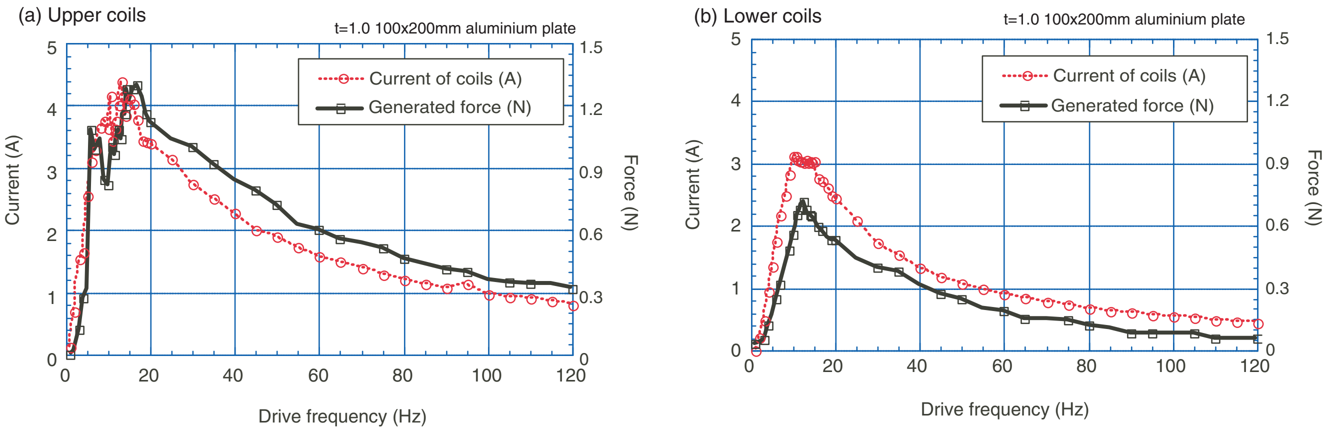


Fig. 4. Performance of current in the coil and translational force

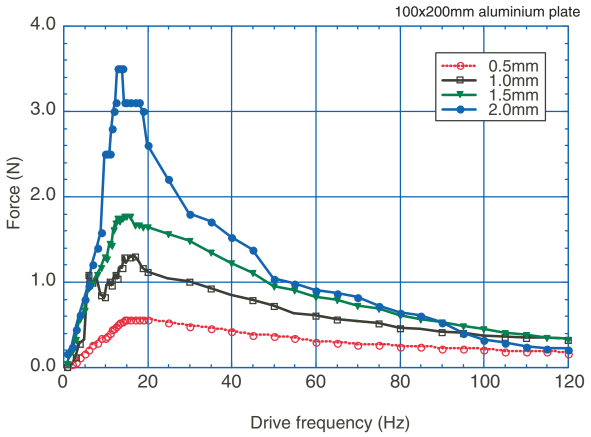


Fig. 5. Translational force on forcers with different thicknesses

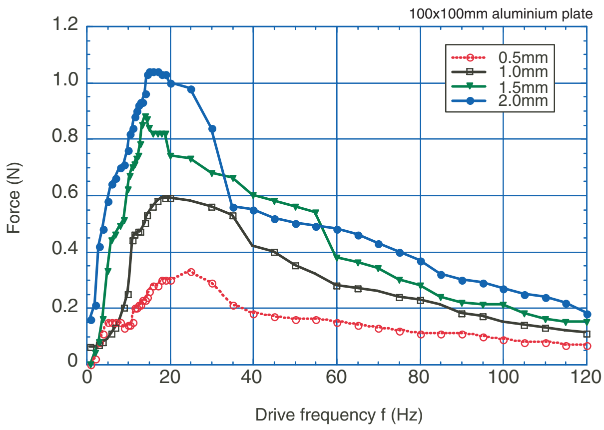


Fig. 6. Translational force on half-size forcers

coils. Many small exhaust holes were drilled in top of the desk, and the emitted air was used as an air cushion for the forcer to reduce friction between the forcer and the table.

5.2. Performance of the trial 2-DOF LIM

5.2.1. Upper coils and lower coils. As mentioned above, the two sets of coils are overlapped, so we supposed that the power of the traveling magnetic field generated by the lower set on the desk would be weaker than that by the upper sets considering the distance between the sets of coils and the forcer. This reduction corresponds to a reduction of generated force on the forcer. Therefore, we measured the translational force generated by the upper and lower sets of coils individually. We used an aluminum forcer with dimensions of 100 x 200 x 0.5 mm at first. The controlled condition is the frequency of the AC signal sent to the coils. Before the experiment, we obtained the frequency at which the LIM can generate maximum force. We recorded the translational force at every 0.5 Hz around the maximum force frequency, and at every 5 Hz in other ranges. To measure the force, we used a spring balance scale, and we also used a clamp meter to measure the current in one of the coils. Figure 4 shows the results. The x-axis indicates the frequency of the AC signal. The left and right y-axis indicates the current in the coil and the translation force on the forcer. As we supposed, the results confirmed that the upper set of coils could generate twice the force of the lower one. In the lower set, the maximum force was 0.72 N at 12.5 Hz, and the maximum current was 3.13 A at 10.5 Hz. In the upper set of coils, the maximum force was 1.30 N at 17 Hz, and the maximum current was 4.40 A at 13.0 Hz. In both coils' results, there is a slight increase in both current and force during lower frequencies and they rise to the peak. Then the curves fall gently. The coils show slightly different electrical characteristics even though we used the same inverter unit in the same configuration for each set of coils. This is due to the individual specificity of each set of coils and the difference of the electromagnetic circuit between the coils. From the results, we confirmed that the translational force could be controlled by the frequency of the AC signal in the coils.

5.2.2. Thickness of the forcer. Next, we focused on the conditions for the forcer. At the low frequency used here, the traveling magnetic field could permeate a few centimeters of the forcer due to the surface effect, and an eddy current was induced within the forcer. In the LIM, the force is obtained from the product of the eddy current in the forcer and the magnetic field strength. From this, we supposed that a thicker forcer would generate a larger force under the same conditions. We measured the force using four aluminum plates with 0.5, 1.0, 1.5 and 2.0 mm of thickness. The dimensions of the plates were 100 x 200 mm and we used the upper set of coils. Figure 5 shows the results. The x-axis and y-axis indicate frequency and translational force, respectively the maximum force was 3.5 N degrees of force using the plate that was 2.0-mm-thick at 13.5 Hz. As for the other plates, the 1.5-mm-thick plate generated 1.72 N degrees of force at 15.0 Hz, the 1.0-mm-thick plate generated 1.28 N at 14.5 Hz and the thinnest plate, the 0.5-mm-thick one generated only 0.56 N degree of force at 17 Hz. In every forcer, the curves show the same trend as the previous results.

5.2.3. Dimensions of the forcer. In addition to its thickness, the eddy current quantity is also influenced by the area of the forcer. We measured the force by using a half-sized aluminum forcer under the same conditions as the previous experiment. The dimensions of the forcer were 100 x 100 mm, and the thickness was 0.5, 1.0, 1.5 and 2.0 mm. Figure 6 shows that the thickest forcer can generate a maximum 1.04 N degrees of force at 16 Hz. As for the other plates, the 1.5-mm-thick plate generated 0.88 N degrees of force at 14.0 Hz, the 1.0-mm-thick plate generated 0.59 N at 19.0 Hz and the thinnest plate, the 0.5-mm-thick one generated only 0.3 N degree of force at 19 Hz. This shows that the half-sized forcer could generate only a third of the twice-as-large forcer with the same thickness.

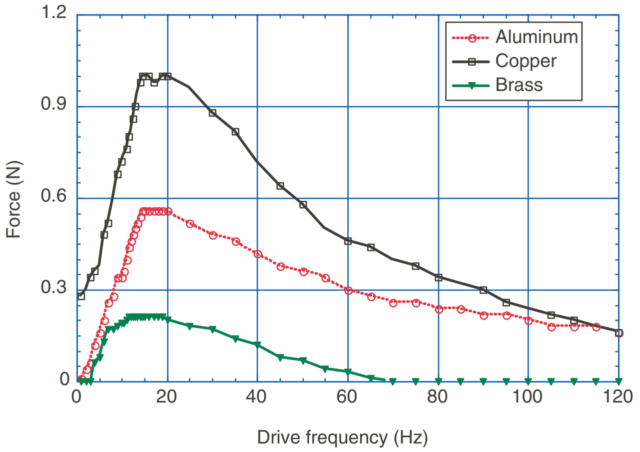


Fig. 7. Translational force on forcers with different materials

5.2.4. Material of the forcer. Moreover, we measured the translational force using different materials for the forcer. As described above, the LIM can employ any kind of conductive, but nonmagnetic material as a forcer. In the experiment, we compared forcers that are made of aluminum, copper and brass. The nonmagnetic permeability of these materials is 1.0. However, the electric resistivity of copper is twice as high as that of aluminum, and the electric resistivity of brass is half that of aluminum. The dimensions of the forcers were 100 x 200 x 0.5 mm and we used the upper set of coils. Figure 7 shows the results using the same manner as previously described. The curves tell us that the copper forcer can generate 1.00 N degree of force at 17 Hz, the aluminum forcer can generate 0.56 N at 17 Hz and the brass forcer marks the smallest force, 0.21 N at 14.5 Hz. From this, we can see that the translational force increases relative to electric resistivity.

5.2.5. Direction control. Next, we did an experiment to verify that the 2-DOF LIM could generate the translational force in optional directions by driving two inverters individually connected to the upper and lower sets of coils. In the experiment, the driving frequency of the upper set of coils was fixed at 50 Hz, and we adjusted the frequency of the lower set of coils to achieve force in the target direction as an experimental condition. We used a string and protractor to measure the direction of the force: one end of the string was fixed to the desk and the other end was fixed to the center of the forcer. Here, the forcer pulled the string in the direction in which the integrated force was generated, and we obtained the degree of the angle by the protractor. The forcer used in the experiment was an aluminum plate with 100 x 100 x 1.5 mm dimensions. The target degree of the angle was from 0 to 50 degrees in 5-degree intervals. Figure 8 shows the results. The curve tells us that the 2-DOF LIM can control the direction of translational force by using

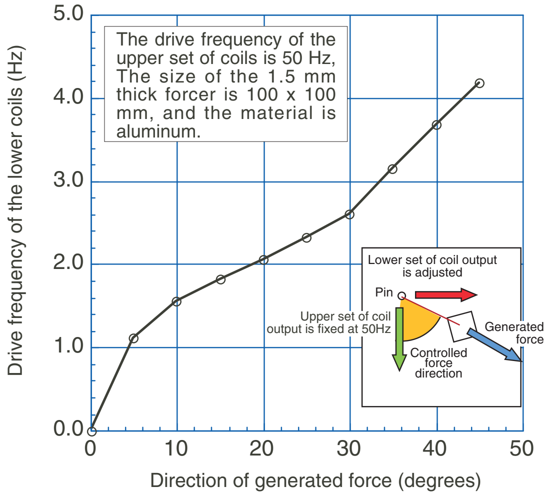


Fig. 8. Controllability of the direction

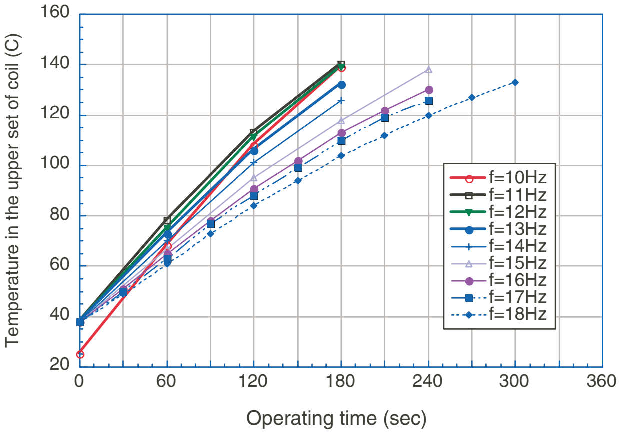


Fig. 9. Thermal condition in steady operation

the frequency control method.

5.2.6. Thermal condition. The weakest point of the LIM is heat. A typical rotary AC motor has a built-in fan to cool itself down. In the trial LIM, the coils are placed inside the core, therefore, they have to be equipped with a forced-air cooling apparatus. To measure the thermal transient of the trial LIM, a small thermocouple thermometer was installed inside of the lower set of coils. To measure the worst case, two sets of coils were driven continuously at the same frequency. The target frequency was selected from 1 Hz to 20 Hz at 1 Hz intervals, and 25, 30, 35 and 40 Hz. Since the maximum rating temperature of the insulated membrane of the coils is 150 degrees centigrade, each measurement was stopped when it reached 130 degrees centigrade. Figure 9 shows only some critical results. When the coils generated maximum force, the maximum current was sent and the temperature reached the operating limitation within three min. Under other frequency conditions, it reached a thermal balance under 100 degrees centigrade.

5.2.7. Conclusion of experiments. From these experimental results, we can conclude that the trial 2-DOF LIM can generate a few Newton degrees of force in any direction using a copper plate with dimensions of 100 x 100 x 1.0 mm as a forcer. Of course we can use only a metal plate as the forcer on the desk, and it will never disturb the visual image by the front projection and seamless direct manipulation of the Proactive Desk.

6. Issues and future work

We were able to clarify some issues of the trial Proactive Desk through the experiments. First, since we employed ready-made inverters for rotary AC motors to drive the LIM, we were able to control only the frequency of the signal. Driving it in a low frequency range, we sometimes observed vibration in the forcer. Even though we could not discuss this issue mathematically, it seems that this is due to the discrete driving method of the digital inverter. The inverter generated an AC signal by pulse width modulation, so it is designed to drive a higher frequency than the range we used. As a solution, we will employ current-control based amplifiers to drive the LIM by using custom made inverter units.

As for the thermal condition, the trial system could not be driven for a long time with maximum performance, as shown in the results. We need to provide a more powerful cooling apparatus for the stator. Moreover, we also have to consider the thermal condition of the forcer. Some of the eddy current that does not contribute to the translational force is transferred to heat, and this accumulated inside the forcer. This is the same principle as that of an induction heating stove in a kitchen. We have to develop a cooling apparatus for the forcer without a troublesome mechanism while preserving the advantages of the LIM.

Moreover, the sets of coils generate the traveling magnetic field uniformly in the entire desk surface in this configuration, and the movable forcer is just a small part. Therefore, the majority of the electric power is discharged as heat and magnetism of no use. Furthermore, the worst weakness is that, when some forcers are put on the desk, the system generates translational force on every forcer according to its material and size in the same direction. Additionally, since the coil pitch of the trial LIM is 45 mm, a small forcer of less than 45 mm cannot ride on the traveling magnetic field and is fixed to a point on the desk.

To solve these issues, we are designing the next-generation Proactive Desk as shown in Figure 10. We will replace the sets of big coils with a number of small coils wound around each column of the stator core, and each coil will be connected to the same number of amplifiers individually. When the motor is operated, a PC will control a part of the sets of amplifiers and coils to generate the traveling magnetic field around the forcer. This means that this system will drive the minimum parts of the coil around the forcer, therefore, lowering the power consumption and improving the thermal condition. Furthermore, two or more

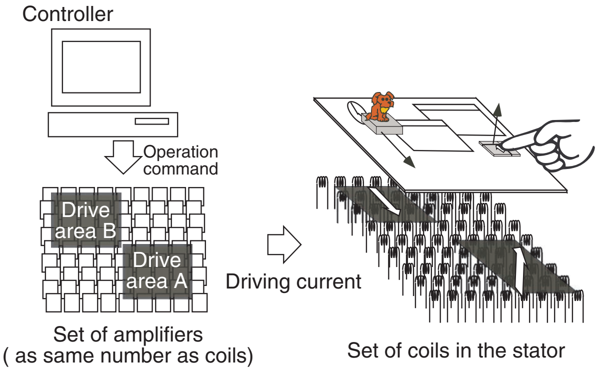


Fig. 10 . The next-generation Proactive Desk

forcers can be driven individually and simultaneously. In this configuration, additionally, all coils will be placed in equal conditions: the same gap and the same magnetic and electric circuit, so that the system will not exhibit any differences such as the difference between the upper and lower sets of coils in the first trial system. Moreover, to achieve a stronger magnetic field, it will be equipped with long columns to increase the number of turns of each coil. Consequently, we can design a smaller coil pitch, so a the smaller forcer, such as an eraser or a pen-shaped force, can be driven on the desk.

7. Conclusion

In this paper, we proposed the Proactive Desk, a new digital desk with haptic feedback for a co-experience web that enables people to share the feelings and experiences of other users via the Internet. We employed a linear induction motor based actuator so as to preserve the advantages of the digital desk. Here, the stator of the motor is built into the desk and the user handles only a small metal plate, the forcer, to feel haptic sensation in the digital desk environment. Therefore our digital desk enables the user to seamlessly handle both digital and physical objects on the desk with a common standard.

We have developed the first trial Proactive Desk. Through an experiment using the trial system, we concluded that it could generate a maximum 3 N degrees of force to the forcer in any direction. We also clarified some issues about the trial system, i.e., stability, thermal condition and multiple forcers control. We also proposed a next-generation system to solve these issues.

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