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Design and Development of a Wearable Haptic Feedback Device to Recognize Textured Surfaces: Preliminary Study

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Abstract— **Tactile sensing is an important biological function. Additionally, not only humans, robotic manipulators also require tactile sensing ability to improve quality of grasping and environment perception. Regarding tele-operated robotics, object manipulation, and surface texture recognition is an important function. These sensor data should be transmitted to the operator correctly so that the operator can evaluate the griping forces, object surface conditions, and edges of an object which are governing factors for manipulation and environment exploration. Force and vibration are the key modalities which required to recognize incipient slip and surface textures correctly. For this purpose, several researches have been carried out to implement tactile feedback actuator systems. In our study, a novel method is introduced for artificial tactile feedback. The device is designed so that it can be worn on the users finger. The experimental setup consists of three pairs of micro gear motors with a belt attached to each pair. When motors in one pair are rotating in the opposite directions, user can sense the feeling of force due to tension of the belt, whilst rotation of the motors in same direction and oscillating the direction frequently gives the sensation of vibration. Having three pairs of motors, which is the specialty in this device, gives the ability to identify the correct contact location of the applied force or vibration, and also it helps for edge detection as well. According to the experimental results, this device can successfully provide combination of force and vibration sensations as well.**

I. Introduction

Tactile sensing is an important biological sensory function of human perception [1]. Fingers and hand are the core contributors of human tactile perception. For grasping and object manipulation, tactile sensing ability of the fingers play a major role [2], [3]. Human fingertips have distinctive sensors called mechanoreceptors to provide tactile sensations [2]. When a human gets in contact with an object, pluses generated from each receptor are sent to the brain via nerves. After processing these raw data by the brain, tactile information pertaining to object properties and surface conditions are derived [1], [4].

Tactile sensation is an important sensory function not only for the humans, but also for the robot manipulators. There can be limitations in the robots usage due to lack of tactile sensation. Robots have difficulty to grasp complex shapes, perform pinch grip and small object manipulations without tactile sensations similar to that of humans. Visual information alone is not sufficient for such tasks. Furthermore, tele-operated robotics is another area which the tactile sensation has become important. Artificial tactile sensation can be introduced to tele-operated robots, enhancing the quality of controlling the robot, when it performs grasping and manipulation tasks. Up to present context there have been number of researches aiming to produce effective artificial tactile sensing systems, though much of these research did not produce viable tactile systems to be used in commercial applications [1], [5]-[7].

Considering the functions of tactile sensation for robots, much of attention should be given to object manipulation. Surface texture recognition is a considerable aspect in this scenario as well [8]. In order to manipulate the said object, its surface conditions needs to be evaluated first. These systems could also be used to classify textures and identify objects. Researches have been carried out to develop tactile sensors which can distinguish surface textures. In [9], a multi-channel soft tactile sensor system with fingerprint structure, which could identify the contact force, location and surface roughness of different surface textures was implemented. A biomimetic fingertip has been implemented using force sensitive resistors and accelerometers in [3] to distinguish seven types of surface textures, comparing the surface textures by detected force and vibration when moving the fingertip on surfaces. A sensing pen was introduced in [8] to identify different surface textures. It was comprised of an piezoelectric microphone covered with a rugged material and the produced sound while sliding on surface textures was used to identify different surface textures. Another research was carried out in [15] which targeted on biomedical applications, used three hall effect sensors to get force and vibration sensations. According to the aforementioned researches, the surface texture recognition mainly depends on the force and vibration induced from the sensors while sliding the finger along the textures [3], [8], [10].

Apart from tactile sensing, tele-operation requires a additional device to generate the sensations felt by the tactile systems at the master controller side. A haptic feedback device which could mimic the localized vibrations and stress/force would be beneficial when converting information obtained from the tactile systems to haptic stimulations via the haptic display.

Taking the requirements for a haptic display for surface texture recognition into account, several researches are done

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to implement actuator systems to mimic the tactile sensation. A wearable haptic device was implemented in [1], which help to guide the robot for object manipulation, through a haptic display. In this experiment, vibrations and orthogonal forces were applied to feel the sensation when the robot touches objects. A piston with a circular cross-section was used to produce the normal stress. Two extrusions of the piston were connected to a Maxon DC (Direct Current) motor by a twisted wire so that the piston could apply a linear reciprocating force to the skin. In their study, a Haptuator Mark II cylindrical vibration motor was used to provide vibrotactile sensations. The experiments have been carried out to detect slippage, moment of contact and move an object from one place to another using visual, static pressure and vibrotactile feedback. Even though this display can give both force and vibration sensations, the contact position cannot be identified and this device was not tested for surface texture recognition.

It is important to consider about the sensing ranges of human mechanoreceptors when designing actuator systems. Hanif et al. [11] has introduced a haptic display, which can generate vibrations ranging from 0.1 to 300Hz, which matched the detection frequency of Pacinian corpuscle mechanoreceptors [2]. Another advantage in this system was that the usage of miniature 304-111 Pico VibeTM 5mm vibration motors, which make the system smaller and wearable. Another method of providing vibrations was using linear resonant actuators (LRAs) and eccentric rotating mass vibration motors (ERMs) [6]. It could model vibrations of 175Hz and from 70Hz to 200Hz respectively. Even though both above mentioned researches could mimic the vibration successfully, absence of force sensation has become a drawback in surface texture recognition.

Regarding miniaturization of the unit up to wearable level, [12] has used three miniature DC motors in their prototype. This had three degrees of freedom (DoF) with a stationary platform fixed on the finger and a mobile platform which can move according to applied forces. The moving platform is actuated by changing the strain of three wires connected to aforementioned DC motors. A device similar to this setup is carried out in [13], equipped with miniature DC motors with position encoders and the three cables were made of ultra-high-molecular-weight polyethylene. The draw back in these systems was that they can only give the force sensation. Force sensations can be given from belt connected to a dual motor system as well [14]. Application of this concept was used for object grasping in [14]. Vertical stress and shear stress induced when grasping an object was mimicked by rotating the motors in opposite directions and same direction respectively.

In order to implement a feedback actuator system to give the sensation of different surface textures, both force and vibration sensations should be considered. If force sensation is absent, the intensity of the applied force on the texture cannot be copied and since humans move their fingers along the surface to recognize the texture, the vibration generated due to the movement is also should be considered. Therefore, the vibration frequency is also an important factor in surface texture recognition. In the above mentioned researches, providing both force and vibration at the same time is not included. Therefore, this research was carried out to discuss the suitability of proposed method to provide both force and vibration sensations at the same time.

A motor system consisting of three pairs of motors is introduced in our system to give the feedback from surface textures, providing both force and vibration sensing. Despite of surface texture recognition, this research has been conducted to perform the contact position identification task as well. Since three parallel belts are used to mimic the tactile sensation at three areas of the fingertip without overlapping, this system helps to identify the contact position. Compared to existing devices with rotating motor pairs with belts, this is a novel method which has the aforementioned ability, which can be used to mimic both force and vibration modalities together.

This paper is structured as follows. Section II explains the methodology followed in the study to mimic tactile sensation and the design of haptic feedback device. In section III, the experimental setup of the fabricated device and the experiments carried out are discussed. Results of the experiment are included in section IV and finally, the conclusion and future work are explained in section V.

II. Methodology

A. Overview of Artificial Tactile Feedback Systems

Overall artificial haptic feedback systems consist of two major units; sensor unit and actuator unit. Input from the robot manipulator is sensed by the sensor unit and signal processing is done before transferring signals to the user. Overview of the process is illustrated in figure 1. In this study, we are focusing on the actuator unit, introducing a

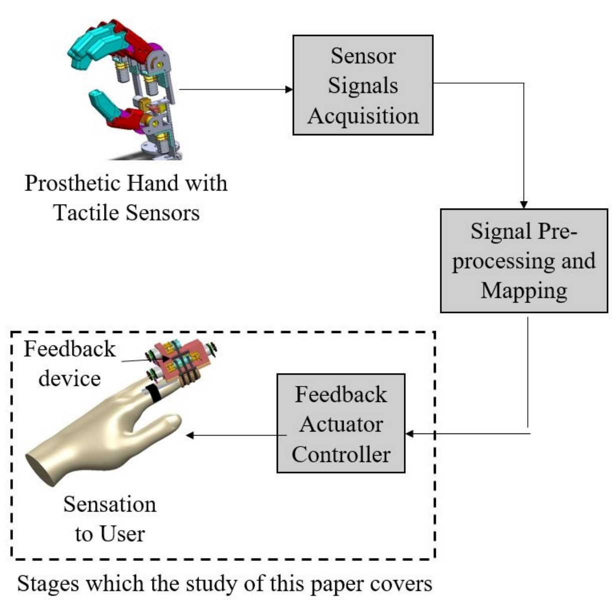
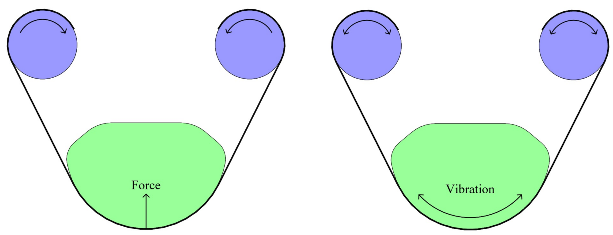


Fig. 1. Overview of proposed Artificial Haptic Feedback System.



(a) (b)

Fig. 2. (a) Demonstration of force sensation by rotating the motors in opposite direction (b) Demonstration of vibration sensation by oscillating the motors

novel method to mimic tactile sensation for surface texture recognition.

B. Design

Fundamental purpose of this study is to determine whether a single system can be used to mimic both force and vibration modalities for surface texture recognition, along with the contact position. We have introduced a rotating motor system to reproduce the above modalities. There, a belt is connected between the shafts of two motors. Rotation direction of the motors and rotation speed are the variables controlled to provide the tactile sensation to the user. Considering one pair of motors, force sensation is denoted by rotating the motors in opposite directions, allowing the belt to tension as shown in figure 2(a). Vibration sensation is denoted by rotating motors in an oscillatory fashion, as shown in figure 2(b). Based on the design requirements, three motor pairs were included in the design, which can give sensation to three areas of the fingertip.

Six identical micro gear motors with encoders were used in this device. Those motors were chosen considering the torque requirement for the application. Selected motors have 900 rpm no load speed which can give a stall torque of 0.0636 Nm. According to the calculations, the motors can generate a force of 15.88 N. Further specifications of the motors are included in Table I. Each pair of motors are connected with an open belt. A fabric belt is selected for this application due to the low elasticity, low friction and high flexibility. The motors are fixed on a motor mount, in such a way that the belts are attached parallel to each other. These belts are 4 mm apart from each other, allowing the user to easily identify the location where the force is applied. Figure 3 shows the complete 3D model of the system comprised with the aforementioned actuators. User can wear the device by inserting fingertip into the finger clip, which has three grooves to guide the actuator belts to limit the movement of belts in undesired directions.

C. Design Features

As mentioned above, the device was designed so that it can mimic force and vibration modalities. For an example, the device can be used to identify the difference between two surface textures shown in figure 4. The gap between two adjacent peaks of the surface profile in figure 4(a) is 10 mm, while the texture in figure 4(b) has 5 mm. If both textures are explored moving the finger at same speed, the textures give two different vibration frequencies. The device should be capable to distinguish this difference. Edge detection and contact position recognition are the special features of this device. As show in figure 5(a), when the finger reaches an edge of the object which it is handling, the user should only feel the locations where the finger is in contact with. Referring to figure 5(a), only the side B of the finger is in contact with the object. To give the corresponding sensation, only belts 2 and 3 should be actuated. Considering a situation as shown in figure 5(b), the finger has explored a spike on the object. This is a situation where recognizing the contact location becomes important. Here, the belt in side B, which is closer to the contact position should be actuated.

TABLE I

SPECIFICATIONS OF MICRO GEAR MOTOR

Speed (No load)	900 rpm
Torque (Stall)	0.0636 Nm
Gear Ratio	30:1
Encoder : Cycles Per Revolution (Motor Shaft)	3
Encoder : Cycles Per Revolution (Output Shaft)	90
Encoder : Countable Events Per Revolution	360
Voltage Range	6V - 12 V

D. Implementation

Structure of the designed haptic device is fabricated using 3D printing, making it easier to wear on finger by reducing the weight to be borne by the finger. The six motors with attached fabric belts are fixed on the motor mount as shown in figure 6. For the control of all three pairs of motors Teensy 3.2 microcontroller development board was utilized. Each pair of motors were driven by a L298N motor driver. Position control and synchronizing of the motors was obtained by controlling the motors using PID (Proportional-Integral-Derivative) control. The specialty in this PID algorithm is that a frequency correction was also included in order to ensure that the motors vibrated at the given frequency.

III. EXPERIMENTS AND RESULTS

Experiments were carried out in two stages to test the capability of the system for surface texture recognition and edge detection. In each experiment, motor rotation angle vs time was plotted to validate the experimental results.

A. Experiment I: Surface Texture Recognition

Since different surface textures have different frequencies when explored with fingertip [3], [8], [10], the device was tested to validate whether it is capable to actuate in different frequencies such that the user could sense the differences for different frequencies. This device is capable to generating vibrations of frequencies from 5 Hz to 10 Hz, which are relevant for rough surfaces. Therefore, to test the performance of the device, 1st, 2nd and 3rd pairs of motors were actuated at frequencies of 5 Hz, 6 Hz and 7 Hz respectively, and the response of the motors were observed by motor

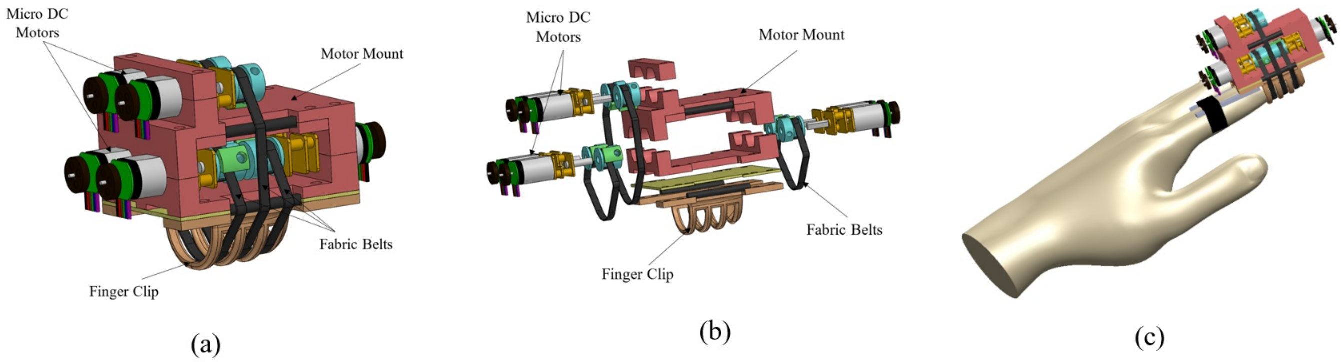


Fig. 3. Design of the wearable Haptic Feedback Device (a) 3D model of haptic feedback device (b) Exploded view of the assembly (c) Device worn on the human fingertip

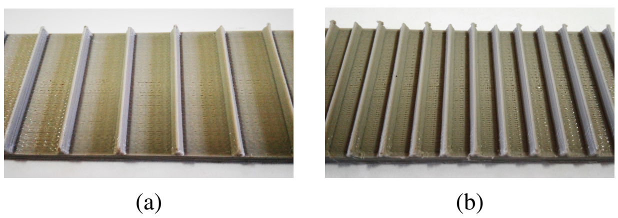


Fig. 4. (a) Texture 1: Spatial period = 10 mm (b) Texture 2: Spatial period = 5 mm

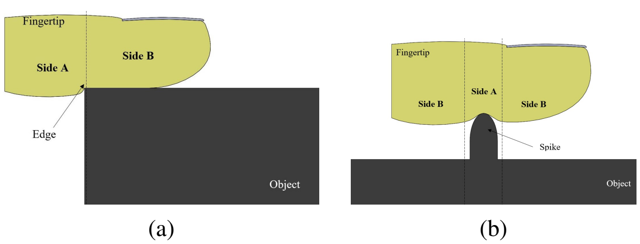


Fig. 5. (a) The finger has reached an edge of the object. Only belts in side B should be actuated and the belts in side A should stop their actuation to provide the proper sensation of this situation. (b) The finger has reached a spike in the explored surface. The method to give this sensation is actuating the belt which is closest to the contact position of the spike, while the other belts stop moving.

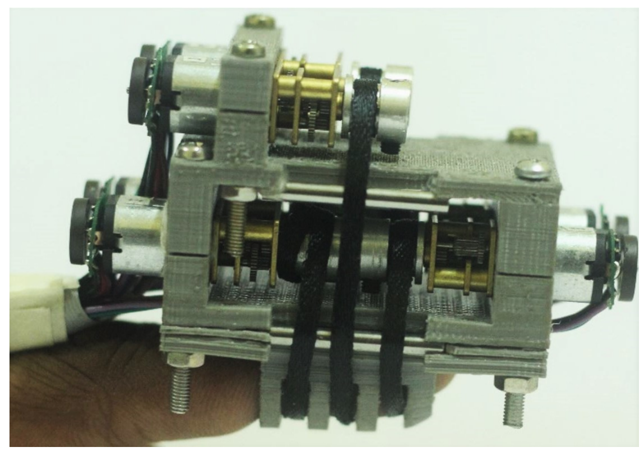


Fig. 6. Fabricated haptic feedback actuator unit is fixed to the fingertip. The unit is fabricated using 3D printing. The finger clip (labeled in Fig. 1) can be changed according to the users finger size.

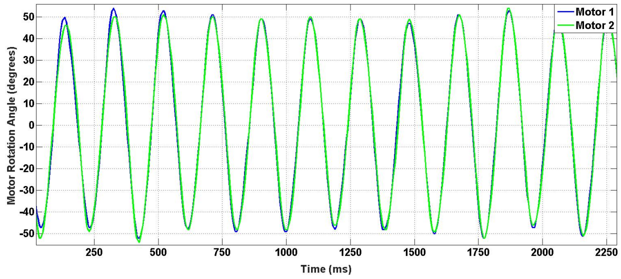
rotation angle vs. time plot as shown in figure 7. For all three frequencies, the motor rotation amplitude was not changed. It can be observed that the three belts are actuated at the given frequencies and the frequency difference is clearly visible in the graphs.

Next step of the experiment was to check whether the system was capable to give force sensation while vibrating. For that, all three pairs of motors were rotated at a frequency of 8 Hz and the belts were tightened by increasing the rotation angle of one motor from each pair, at the instance where the force is given. Then the middle positions for vibration of the motors were changed according to the new configuration. Belt displacement vs. time plot in figure 8 shows how one pair of motors behaved at this situation. Up to time $t1$, the motor pair was only vibrated at 8 Hz frequency. Between $t1$ and $t2$, a force was input to the system. According to the plot, positions of motors are shifted apart from each other and the middle position of two motors are changed. After the force was applied, the motors were vibrating with respect to the new middle position, without changing the given frequency.

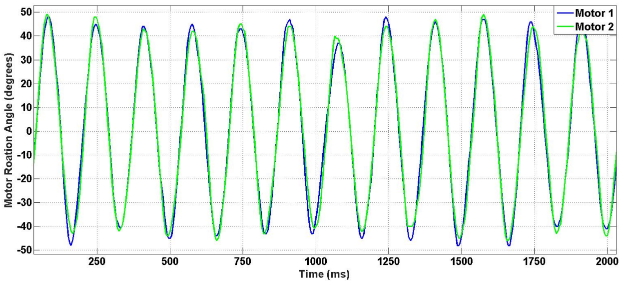
B. Experiment II: Edge Detection

Considering a situation as shown in figure 9(a), when the finger reaches an edge while moving along a surface, it is important to have the sensation of the moment when each portion of the finger has lost its contact with the surface. Since we have used three belts in our device, it helps the user to get the feeling at three distinct areas of the finger. Therefore, when each portion moves beyond the edge, the corresponding belts are stopped.

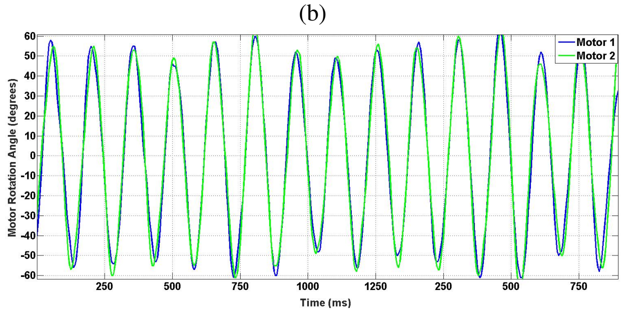
In order to validate the aforementioned ability of the device, a simulated result was taken. Finger movement is started keeping the whole finger on the textured surface. When the finger starts moving, all three belts should be actuated. At the simulation, we used 6 Hz for all three belts. At the moment when the area of the fingertip corresponding



(a)



(b)



(c)

Fig. 7. Vibration response of three motor pairs Motor rotation angle vs. time (a) Behavior of 1st pair of motors when a frequency of 5 Hz is applied (b) Behavior of 2nd pair of motors when a frequency of 6 Hz is applied (c) Behavior of 3rd pair of motors when a frequency of 7 Hz is applied

to belt 1 reaches the edge, that belt should be stopped while other two are moving, providing the sensation to the user, that the first area has reached the edge. Then, when finger is moved further to the same direction, belt 2 also should be stopped when the corresponding area reaches the edge. At the time when the whole fingertip moves beyond the edge, all three belts should be stopped. Belt displacement vs time plot was taken according to the simulated results, as shown in figure 9(b).

Contact position identification against a spike on the surface also can be simulated, assuming belt 1 contacts with the spike first and belt 2 and 3 gets into contact when moving the finger further. To mimic this situation, tension of the belts should be increased when each of the areas contact the spike, so that the spike can be detected by the area on the fingertip where the spike is in contact with.

These results show the effusiveness of the proposed feedback system. Therefore, if a sensing system can properly distinguish the surface conditions along with contact position identification, this setup should be able to mimic them, providing the sensor feedback to the user.

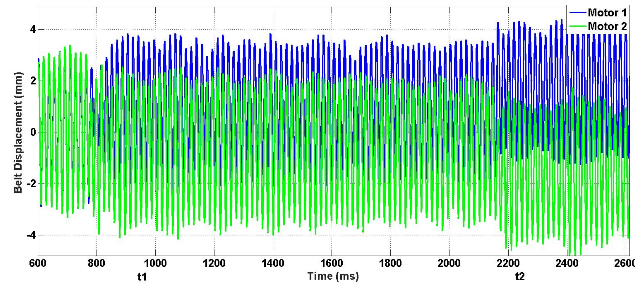


Fig. 8. When a force sensation was given while one pair of motors are vibrated at a frequency of 8 Hz. After force is applied, motors change their middle position with respect to the new situation. Up to $t1$: Only 8 Hz vibration; From $t1$ to $t2$: Force with vibration; After $t2$: Increased force

IV. Discussion

The introduced novel device successfully achieved the research objectives, by representing force and vibration modalities. Even though the whole system began to vibrate due to three different frequencies, the fabricated system proved that the proposed method is acceptable. We believe that the vibration can be reduced by using smaller and precision DC motors.

The wearable haptic feedback device introduced in this paper has the ability to mimic the forces and vibrations, which can be used for surface texture recognition. According to the results of experiment I, the system could successfully mimic the given vibrations and forces.

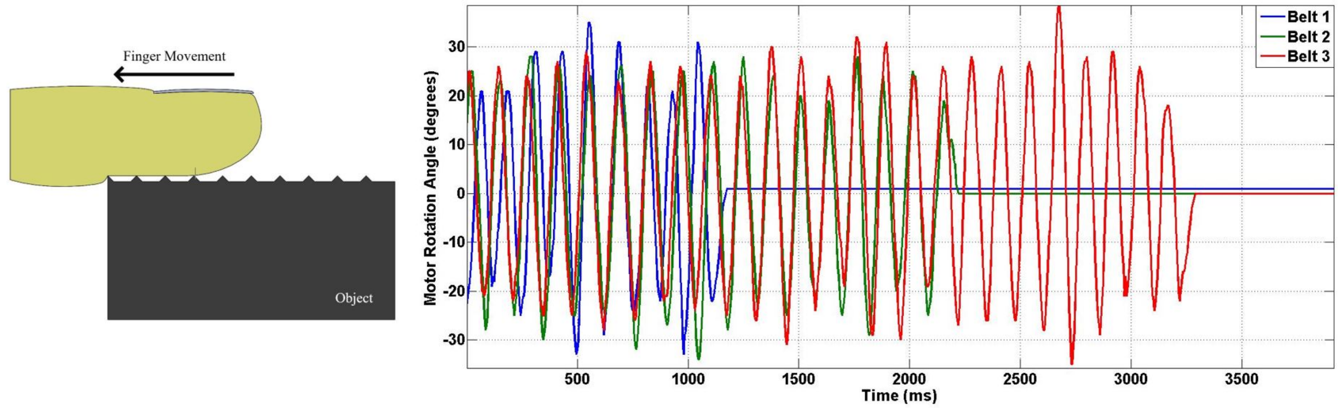
Apart from the surface texture recognition, this device can be used for edge detection in object manipulation. Including three belts connected to three pairs of motors has made it possible to obtain the above tasks. Experiment II was considered to evaluate the ability of edge detection.

The belt material that we used was fabric with low elastic property, which was necessary to eliminate the effects of elongation due to elasticity.

Due to the low rpm and high inertia of the motors, the system could only get frequencies from 5 Hz to 10 Hz. We used those motors because they can give the required force for the system. Due to this frequency limit, the system is capable to identify rough surfaces, but not fine surfaces, since they have higher frequencies. This issue can be overcome if high rpm motors are used.

V. Conclusion and Future Work

This paper proposes a novel haptic feedback device developed using pairs of motors and non-stretching belt drives. The DC motors with encoders were controlled using PID control and could achieve vibration frequency of maximum 10 Hz, which is acceptable for rough textures. due to the method of controlling the belts, we could achieve force sensation as well as vibration sensation. Due to the individually controlled three pairs of motor assemblies, three distinct sensations could be achieved simultaneously. This being the novel feature, more complex sensations could be realized using the proposed system. Furthermore, the contact position and contact situation identification is another advantage of



(a) (b)

Fig. 9. (a) Situation when the finger reaches an edge while sliding on the surface. (b) Simulated result for edge detection while exploring surface texture. While sliding along the surface, Belt 1, 2 and 3 are stopped when they reach the edge

this device. Additionally, this device can also detect edges of an object. It is a useful ability for object manipulation tasks. The three belts configuration has made it possible to obtain the above ability.

The device can be further developed by making it a smaller in size in order to easily be worn by the fingertip. The belt material which is more suitable for the device should also be chosen in order to get more accurate representation of the sensations.

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