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Tactile interface for stimulation of fingertip via lateral traction.

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Abstract:
Tactile displays are gaining recognition as new human-machine interfaces. This paper present a low-weight, single-axis tactile interface designed to stimulate the fingertip through lateral traction. It operates with two ultrasonic linear motors able to move a small plate in contact with the user's fingertip. This miniature interface is capable of a wide range of stimulation signals due to its high force output (0.6 N), its long throw (3 mm) and its high speed (13 mm/s). This interface is driven under closed loop control employing a Hall-effect sensor for position measurement. A model and experimental results will be presented.

Keywords: tactile interface, ultrasonic motor, high-force output, low power consumption.

Introduction

Electronically controlled tactile stimulation is increasingly used in consumer devices such as mobile phones and gaming consoles. The dominant mode of stimulation is the vibrotactile stimulation, which can be delivered to the user by a small DC motor fitted with an eccentric mass [1]. By construction, the frequency and the amplitude of the tactile stimulus given by these motors cannot be set independently and therefore these stimulators are not suitable for rich tactile stimulation. One other approach is to use voice-coil linear motors as in [2] which can operate as flat-band Laplace force transducers. Despite their performance, magnetic technology impacts on the weight of these actuators. This paper describes a new, low weight, single-axis tactile interface comprising a linear stage actuated by two piezoelectric "Squiggle motors" from Newscale Technologies Inc. The interface induces tangential deformation of the fingertip by direct contact with the skin through displacement of the plate (e.g. [3]). We present in this article a prototype of an interface designed according to the state of the art tactile requirements. It is constructed around two ultrasonic motors, which provides larges forces for small dimensions.

Tactile requirements

Stimulating touch by lateral traction of the fingertip allows reproducing a variety of sensation like friction forces, slippage or object weight when gripping [4]. During lateral traction, the fingertip exhibits a mechanical response that can be modeled by a spring of stiffness 0.5 N/mm associated with relaxation and creep effect as explained in [5]. Net lateral deformation of the fingertip pulp can be higher than 2 mm. On the perceptual side, mechanoreceptors embedded into the skin are sensitive to stimulation from quasi-static to 400 Hz. Amplitude threshold are roughly 100 μm for the range DC to 30 Hz and decreased to 1 μm at 250 Hz [6]. The tactile stimulator was designed with these requirements in mind in order to provide a rich panel of stimulations.

Ultrasonic motor

The Squiggle motors (shown in Fig. 1), a millimeter size linear actuator, ensure the mechanical motion of the interface. Their stator comprises four piezoelectric ceramic plates attached on each face of a rectangular nut. These ceramic plates are actuated cyclically to create a turned vibration that causes a wobbling motion of the nut. The motion is transmitted by friction into a rotation of the threaded axis. Because of its threaded geometry, the rotor undergoes a fixed-axis screw-motion [7]. The tip of the axis is rounded so it can push on a surface causing linear motion without being constrained in rotation. Similar motor based on rotational bending motion, without threaded transmission [8], or in bigger dimension have been developed over the years [9].

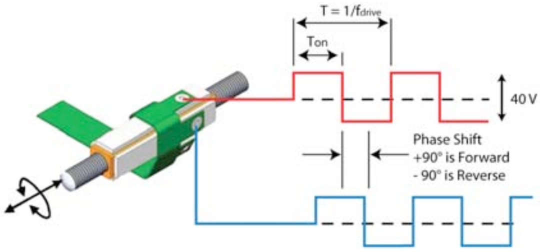

***Fig. 1**: Squiggle actuator principle of action and electronic control. Figure adapted from Newscale technologies materials.*

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A square voltage signal is applied to the piezoceramic elements that cause the wobbling motion of the nut. This frequency is fixed to $f_{drive} = 170$ kHz, which corresponds to an optimal efficiency. The energy transmitted to the actuator can be adjusted by changing the duty cycle ($\alpha = \frac{T_{on}}{T}$) of this square signal or by reducing the maximum voltage. As these high voltages are often generated by charge pump, the time response of this driving method can be long. Consequently, PWM driving solution, which adjust the duty cycle of the signal, is preferable. The phase shift affects the direction of the motion.

The performance of this actuator is compatible with tactile stimulation requirements since its stroke is up to 6 mm and its maximum speed is $v_{\max} = 10$ mm/s. This enables peak-to-peak displacement governed by the relation $\delta_{pp} = v_{\max} . f^{-1}/2$ and produce vibrations much above the tactile detection threshold in a large dynamic range. To ensure that the stall-force is sufficient to deform the skin over a large stroke the present device configuration includes two of such actuators.

Design

The prototype device can be seen in Fig. 2. The ultrasonic actuators (A) push a slider (B) guided by a linear stage resting on three sapphire hemispheres (C) that slide on a hard-steel grooved path (D) on one side, and on the frame (E) on the other. It can be verified that this configuration creates an isostatic one-dimensional guide made of five lower pairs creating five constraints. Since the constraints due to the contacts are unilateral, a magnet (F) placed on the slider creates a spring-like biasing force to stabilize the assembly. As the slider moves, it shears the fingertip providing a tactile sensation, which is very similar to the stimulation applied to fingertips during normal manipulative and exploratory movements. The fingertip elasticity preloads the motors, eliminating the need for biasing springs. A Hall effect sensor (G) responds to the magnet's field embedded in the slider. The signal is used to determine the position of the slider through a calibrated polynomial approximation. The present prototype is 20 mm long, 30 mm wide and 4.5 mm thick and weighs 4.1 g.

The motors are inserted in a rail inside the frame that reduces the degrees of freedom to 2. A lock is placed on the frame to suppress the linear degree of freedom left by the rail of the frame and a flexible cantilever press the motor inside the rail with a force around 0.8 N to lock the motor. Precision rods ensure the alignment of the assembly.

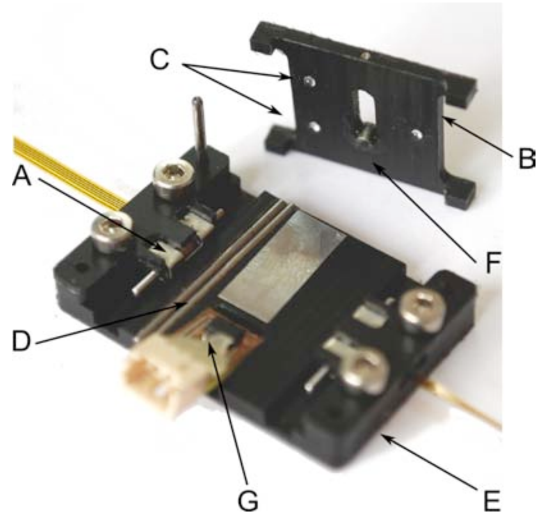

Fig. 2: *Exploded view of the tactile actuator assembly. The dimension are 30 × 20 × 4.5 mm.*

The interface is powered by a custom electronic board, that rely on the specially designed ASIC provided by Newscale Technologies. This ASIC generate high-voltage fixed-frequency signals sent to the piezoelectric plates, their pulse-width modulation and the phase delay. One of this ASIC can drive two of such motors. A microcontroller translates command from USB or analog input into the i2c protocol of the ASIC. The 12 MHz clock frequency of the microcontroller can refresh the velocity of the motors at a frequency above 2 kHz.

Open loop Performance

Performances of the tactile interface have been measured with the help of an experimental setup. The interface is placed on a 6-axis force sensor Nano 17 from ATI Industrial to measure interaction forces between the ground and the slider with a 10 mN resolution. A non-contact laser telemeter LC2100 from Keyence, which has a 0.1 µm resolution, measures the position of the slider. Position, velocity of the slider, along with loading forces can be sense by the setup, which helps determining the speed/tangential force relationship, the duty-cycle/speed function, the friction coefficient of the bearing, and the frequency response of the interface.

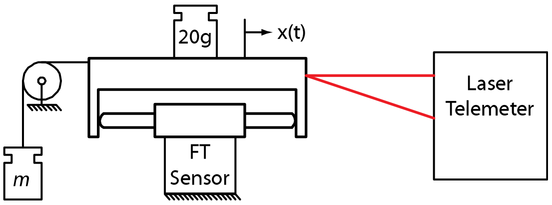

Fig. 3: *Experimental setup for speed measurement.*

Speed/Tangential force. First the relation between the speed and the tangential force applied to the system had been determined with the help of the setup shown in Fig. 3. A mass, *m*, was suspended to a thin wire hocked to the slider. This mass applies a tangential force on the slider. An additional mass of 20 g was put on top of the slider to ensure a constant pressure on the bearing. A 1 Hz square signal was sent to the controller as an input motor command for maximum speed. The actual speed was measured by differentiating the position measured by the laser telemeter. To avoid the noise due to differentiation, a moving average filter on a 5 ms window was applied to the position data before the velocity calculation. Masses *m* from 5 g to 55 g where successively used and the mean speed when the interface was lifting the mass was recorded. This led to the graph presented in Fig. 4. The linear regression indicates that the interface is capable of a stall force of 0.6 N and a no-load speed of 13.2 mm/s. The velocity at maximum duty cycle activation can be estimated as following the relation:

$$v = v_{\max} - \frac{v_{\max}}{F_{\max}} \cdot |F_t| = 13.2 - 22 \cdot |F_t| \text{ for } |F_t| \leq F_{\max}$$

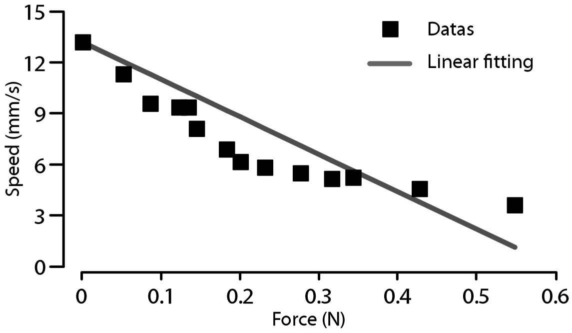

Fig. 4: *Evolution of the speed as a function of the tangential load. The input command is saturated.*

Velocity/duty cycle. The second set of measurement was intended to verify the linearity of the velocity regarding to the duty-cycle α of the signals feeding the motors. This was measured with a 2 Hz sinusoidal signal sent as a command to the interface. No tangential load where applied on the slider. A 20 g mass was glue on top of the slider to ensure its stability. The measurement and the linear fitting are presented Fig. 5. The sign of the duty-cycle is to be interpreted as the phase shift between motor signals. From this measurement, one can derive a lumped-parameter model that approximates the behaviour of the motor:

$$v = \left(1 - \frac{|F_t|}{F_{\max}}\right) \cdot v_{\max} \cdot 2\alpha$$

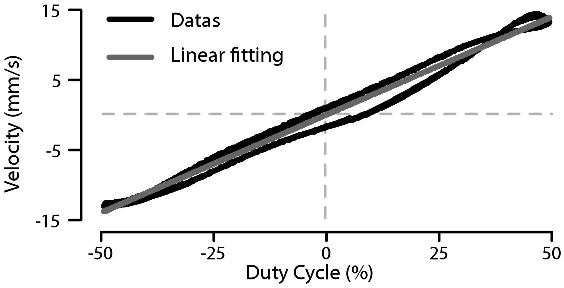

Fig. 5: *Relationship between activation and velocity.*

Bearing friction. Friction of the sapphire hemispheres on the frame has been determined by recording normal and tangential forces in combination of the speed when stroking the slider on the frame in the absence of motors. Measurements plotted at Fig. 6 show that the friction force of the bearing follows a Coulomb law,

hence $\frac{F_t}{F_n} = 0.15 \times sign(v)$.

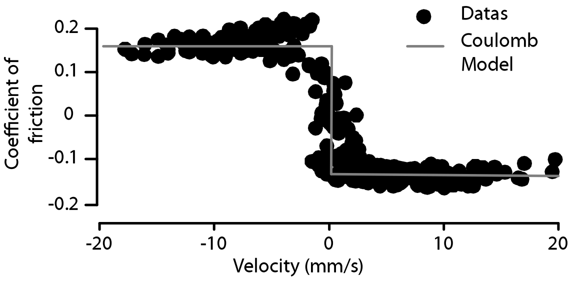

Fig. 6: *Coefficient of friction of the slider on the frame as a function of slider speed and the proposed model.*

Considering that a finger applies on average a 1 N normal load on the slider, the friction force will be as low as 0.15 N. The motors can provide enough force to overcome this friction force.

Frequency response. Finally, the frequency response of the interface was acquired by sweeping sine-shaped duty-cycle commands of increasing frequency from 1 Hz to 30 Hz and of maximum duty cycle amplitude. Measurement of the position amplitude output and the phase delay are presented at Fig. 7.

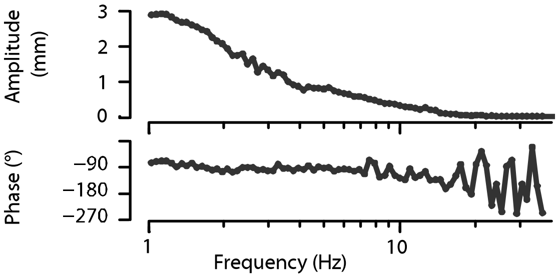

Fig. 7: *Open-loop frequency response of the interface.*

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The stroke amplitude is decreasing as the frequency increase. Above 30 Hz, the none-loaded response becomes null and therefore the stimulation is imperceptible. The cause might be the backlash between the motors axis and the slider contact plate. Nevertheless, the interface can provide a perceptible sensation from DC to 30 Hz.

Closed-loop Control

Since the actuators are speed-controllable, we used closed loop control of the slider position to ensure the deformation of the finger. This loop was implemented on the main microcontroller and runs at 2 kHz

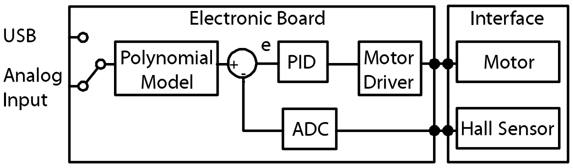

Fig. 8: Control loop scheme

Diagram of the closed-loop control is shown at Fig. 8. The setpoint is read by the control board from analog input or usb. The setpoint is compared with the measured position to calculate an error e. A PID controller sends velocity command to the motor driver. A Hall sensor measures the current position of the slider equipped with a magnet. The Hall sensor voltage is read by a 10 bit analog to digital converter (ADC).

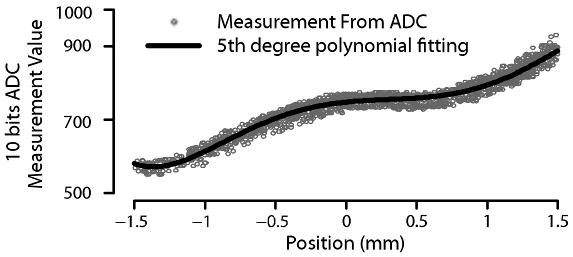

Fig. 9: Polynomial fitting of the hall sensor measurements.

The relation between the position and the sensor is not linear so the ADC measurements have been calibrated with the laser telemeter to create a 5th degree polynomial approximation that converts desired position into digital value (see *Fig. 9*). With this hall sensor and its ADC, the interface can achieve a 10 µm positioning resolution.

Conclusion and outlook

The 0.6 N stall force and the 3 mm stroke are well suited for quasi-static stimulation like static contacts, grips and a number of haptic effects operating in the low frequencies such the simulation of small virtual bumps and features [10]. However the low frequency cut-off makes them incompatible with the simulation fast tactile events such as roughness or slippage. To overcome this issue, one could propose to combine the present actuator technology with another having a smaller stroke response but which could respond to faster signals, i.e. from 30 to 250 Hz.

In order to provide even richer interaction, a 2-degrees-of-freedom version is in preparation. This interface will be able to shear the fingertip in both directions with the same performance that the one presented in the present article.

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