Sensorglove - a New Solution for Kinematic Virtual Keyboard Concept

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Abstract–**We consider limitations of conventional keyboard in regard to compact mobile communication devices or computers and discuss performance of recently introduced accomplishments of the concept of kinematic virtual keyboard. Relaying on their shortcomings we propose a new solution, which strictly involves the principle of particular correspondence between sensor state and symbol, where each independently movable finger joint activates its own sensor, with a substrate in the form of glove to associate all these numerous sensors. On the contrary to complex tactile or gyroscopic sensors applied in these devices we propose very simple designs of extensive and compressive sensor with very linear conversion characteristic. Two typing styles are considered and related principle of symbol-sensor correspondence, implying definition of joint functional capability. Finally, we consider the prospect of the concept itself.**

Index Terms–**Hand kinematics, Human-machine interface, keyboard, sensors, virtual keyboard**

I. INTRODUCTION

IF we consider the computer keyboard as a direct heritage of typewriter we may think of it as the best shape of symbolic entering device, since the typewriter's disposition of keys, being the result of "ergonomic evolution", best suits the man anatomically-functional properties.

Miniaturization of mobile processing-communication devices has made the issue of man-machine direct interfaces (keyboard/display) more critical. At first, the efforts were directed to make it as compact as possible, with tolerable losses of its functionality and use convenience, until the bottom of the anthropomorphic barrier was reached, imposing the search for new concepts.

On the other hand, the process of seeking for a new conceptual "keyboard" should not reduce, for the sake of compactness, but preserve its full functionality*, because of rising device's processing capabilities. Here a paradox appears, when the man itself seeks for as small as possible devices, which would be very handy and unnoticeable to carry but fully convenient to use, while, at the same time, imposes limitations by its huge hands and limited visual abilities. Obviously, it is possible to produce extremely miniature full qwerty keyboard and screen (equivalent of e.g. 15''-displey), but there would be no one to type on it and to see it.

In the following we will briefly consider a new concept of kinematic virtual keyboard. Here we omit discussion about another part of man-machine direct interface - display. Also, touch screen keyboards, which can be activated by stylus, as on any PDA, or joystick, as on e.g. PC Watch, Matsucom Inc., [1] are not considered here.

II. THE HAND-KEYBOARD KINEMATICS

Although the typing is seemingly parallel key manipulation it is in fact sequential, as a consequence of language sequential structure. Parallel access to keys serves just to speed-up the (sequential) typing rate. In that way, very complex movements of fingers and hands are converted into stream of symbols. Apart from being a converter, the keyboard has also a guiding role - to show the user where to place the right strokes, which is very helpful especially for low-trained users.

The hand can be considered as a complex kinematic/dynamic system comprising five simple open kinematic chains [2], where each one includes 3 kinematic pairs (Fig.1). In that way, a particular spatial disposition of joints J_{ij} and links $\Delta l_{(i+1)j}$ can be related ($T(p)$) to corresponding disposition (two-dimensional K_{mn}) of stroked keys on the keyboard:

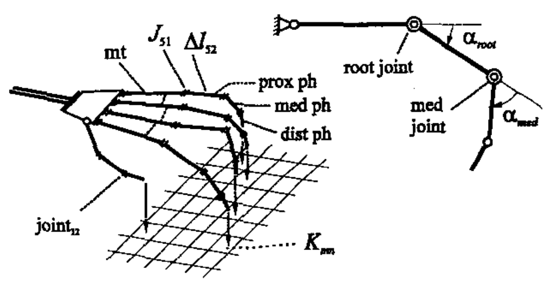

Fig. 1. Kinematic model of human hand with joints J and links Δl. The arrows show mapping of hand posture into specific set of symbols i.e. labeled keys on keyboard. Kinematic chain of one finger includes: metacarpus [mt], proximal phalanges [prox ph], medial [med ph] and distant one [dist ph]. Active (root and medial) and passive joint are shown in graphically different way.

$$^{(p)}\left[\Delta \bar{l}_{ij}\right]_{i=1,j=0}^{5,3} \xrightarrow{T(p)} {}^{(p)}\left[K_{mn}\right]_{m=1,n=1}^{M,N} \tag{1}$$

where

$$\bar{r}\left[J_{ij}(x,y,z)\right] + \Delta \bar{l}_{i(j+1)} = \bar{r}\left[J_{i(j+1)}(x,y,z)\right] \tag{2}$$

Typing skill of the user (p) determines the maximum number of stroked keys and the effectiveness of conversion $T(p)$, since certain very complex hand pattern of $[J_{ij}]$ or $[\Delta l_{ij}]$, which complexity would give full combination of symbols, yields only one activated key.

Nevertheless, here is an invariant: each user, regardless its skills, types the intended key unmistakably because labels on keys guide its intentional finger movements.

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III. Existing Concepts of (Virtual) Keyboard

A. *The Classic Keyboard and its Derivatives*

The term 'keyboard' is referred to as device with several tens of keys labeled with appropriate (alphanumeric) symbols. This concept has been taken various appearances on many mobile devices (wearable PC, mobile PC, PDA, mobile phone) such as: Wearable IBM PC (with 39 keys) [3], Twiddler chorded keyboard with 12 finger and 6 thumb keys [3], Sony VAIO Picturebook (87), qwerty drawer keyboard in Sharp Zaurus I-geti PDA (37 keys), Nokia 9210 (61), Motorola Accompli 009 (53), Motorola V100 (43), Nokia 5510 (48) etc. Also to mention the Think Outside Palm Portable Keyboard [4] as an attempt to store big in small.

B. *New Concepts of Keyboard*

There is a redundancy in the whole process: key strokes are just formal confirmation of precedently prepared hand posture. In other words, a disposition of activated keys already exists in finger disposition. This was the basis for a new concept of symbolic entering device - to eliminate the keyboard itself and to place its function in human hands movement, without auxiliary device(s) that serve just for confirmation. Hence, in all such concepts there a problem arises how to detect fingers movements and to recognize the "typed" symbols. Two approaches are at our disposal - mechanical and/or optical.

New concepts of keyboards include Lightglove [5], Ericsson's Senseboard [6], and Samsung's Scurry [7], developed as wearable keyboards for use with PDAs.

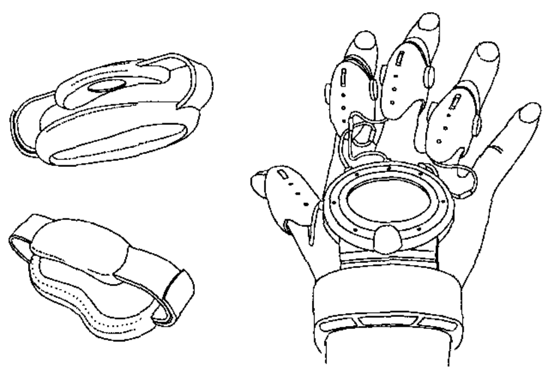

Fig. 2. The pair of devices that make Senseboard keyboard, observed from two angles (left). Outer look of Scurry, shows four attached sensor moduli wired to the central processing module (right).

The Senseboard device, a soft rubber pad which the user simply slips onto each palm and start typing as if a keyboard was in front of him. A demo of the product, presented at the Comdex 2001, didn't work so well, however, and produced the gibberish "DNiSP" when the tester was asked to type "Comdex". It is not surprise as it assigns (recognizes) a symbol to the whole disposition of finger tendons and palm muscles, which are detected through the thick palm tissue and hence inevitably smeared.

Samsung's Scurry works by attaching motion sensors to middle finger joints. It doesn't detect muscle movement, but rather uses gyroscopic technology to detect angular movements of fingers through space. This approach works better. Generally, these gadgets belong to the category of kinematic virtual keyboard. Obviously, the attribute "kinematic" stems from finger movement detection, while "virtual" means that the symbols are right within fingers. However, both devices are too bulky, and smaller nonfunctional prototypes are expected.

Both models are wired for now but the future ones will support the Bluetooth. Also, both products require specialized software for handheld devices. For example, Senseboard software includes a dictionary program that predicts words based on common grammatical sentence structures to boost keying accuracy, by which the designers indirectly confirmed its ineffectiveness.

The Senseboard comprises two extra (mobile) moduli besides the main mobile device (PDA or smarthphone). The main intention of Senseboard designers was the minimal number of extra mobile devices but they reached small typing correctness. In the Scurry, with even ten additional mobile moduli the situation is opposite. Its separated sensors detect more defined mechanical quantities, while the Senseboard sensors detect a "crowd" of features..

Obviously, there is a tradeoff between the number of extra moduli and correct typing rate.

IV. More Sensors in Few Moduli

If we accept as unavoidable the fact that an additional gadget must accompany main mobile device there still remain serious shortcomings of presented prototypes, including intolerable typing ambiguity and high level of uncertainty, caused by the fact that a pretty entangled joint-link pattern is, as a whole, transformed into set of symbols. The user must know how to set up its fingers for desirable set of symbols, meaning a lot of practice, since in this case there are no referent labels on keys.

Therefore we propose a solution that would reduce uncertainty and improve effectiveness. The author's idea dates back to January 2001, when its further development was interrupted until reactivation after appearance of similar concept designs on Comdex 2001.

Hand shape variability stems from variability of joints coordinates and angles of kinematic pairs, i.e. phalanges. As opposed to joint coordinates, the angle of a kinematic pair is unambiguous parameter and posses essential invariance. Therefore, we relay the functioning of proposed virtual keyboard exactly on the angles, finding additional confirmation for that choice in its simpler measuring.

The human hand represents a bundle of 5 kinematic simple open chains (of metacarpus (mt) and phalanges (ph)) which lateral anatomic connections make them partly independent [8] (Fig.1).

Metacarpuses of four fingers are strongly interconnected forming the palm plane and are able to make slight lateral collective spreading movement. On the other hand, finger kinematic pairs i.e. joints: [mt]-[proximal ph] and [proximal ph]-[medial ph], are separately and independently movable, while the joint [medial ph]-[distant ph] is a passive joint or a follower (Fig.1).

Each chain can be easily described by a model based on Denavit-Hartenberg notation [2]. Regarding the selected functioning principle in this case, such modeling is not necessary because only angles are important. In addition, kinematic modeling of robotic system has a purpose in subsequent modeling and synthesis of artificial manipulator movement. But here we consider a system which generates movement by itself and willingly selects its spatial patterns so the "robotic" analysis is superfluous. Consequently, the mathematical formalism could be quite simple.

Relying on such anatomically-functional analysis of the hand, controllable joints are identified, so there are 4x2=8 locations or mutually independent actuators on fingers, where we neglect partial dependence between ring and little finger. For simplicity, we will consider all joints as revolute, except partially spherical thumb's joint [Os trapezium]-[mt]. Hence, the thumb itself brings 4 actuating locations more: 2 on [Os trapezium]-[mt] joint (left-right and forward-backward movement), 1 on [mt]-[proximal ph] (which can be neglected) and 1 on [proximal ph]-[distant ph], making total of 11 actuators (Fig.1).

If we assume that between 50-60 keys make a minimal keyboard, each actuator-joint of one hand should have 60/11=5 distinguishable states. Stating that the average angle range of a finger joint is about 90 degrees (α in Fig.1) that makes an increment of about 20 degrees per state and gives sufficient margin to the user.

Two hands comprise 2x11=22 actuators so 60/22=2.7, giving 3 different states-angles α_{kl} and a margin of $\Delta\alpha$=90/3=30 degrees.

Therefore, one sensor should be attached at each joint to measure its angle. Instead of pretty complex gyroscopic sensors [9], we propose much simpler ones.

V. Design of Sensors

The joint angle can be indirectly measured through the extension of corrugated skin over the joint caused by its bending. Also, we may use layer compression of a belt made of some fabric and pulled over the joint. So, we distinguish extensive and compressive sensors.

A. *Extensive Sensor*

It is shaped as a strip made of elastic electroresistive material. Fig. 3 (a and b) schematically shows its functioning. The bending of a joint causes strip deformation (extension, narrowing and thinning) and a proportional change of strip resistance. From an equivalent linearised scheme it is easy to write relationship

$$R(x) = \rho\frac{l(x)}{A(x)} = \rho\frac{L_0 + \Delta x}{V_0/[L_0 + \Delta x]} = \frac{\rho}{V_0}[L_0 + \Delta x]^2 \qquad (3)$$

or

$$R(x) = R_0\left(1 + 2\frac{\Delta x}{L_0} + \frac{\Delta x^2}{L_0^2}\right), \quad x \geq L_0 \qquad (4)$$

Taking into account the relation $\Delta x = r\alpha$ (Fig. 3. (a,b))

$$R(x) = R_0\left(1 + 2\frac{r\alpha}{L_0} + \frac{r^2\alpha^2}{L_0^2}\right), \quad \alpha \geq 0 \qquad (5)$$

Regarding power consumption we may consider its capacitive variant, where the largest strip facets are metallized. Assuming that the strip volume remains the same during deformation the change of capacity would be

$$C(x) = \varepsilon\frac{S_x}{D_x} = \varepsilon\sqrt{\frac{W_0}{D_0}} \cdot x \qquad (6)$$

Square member in (5) is negligible up to even 50% deformation. Therefore, in both cases we find high linearity of the sensor characteristic.

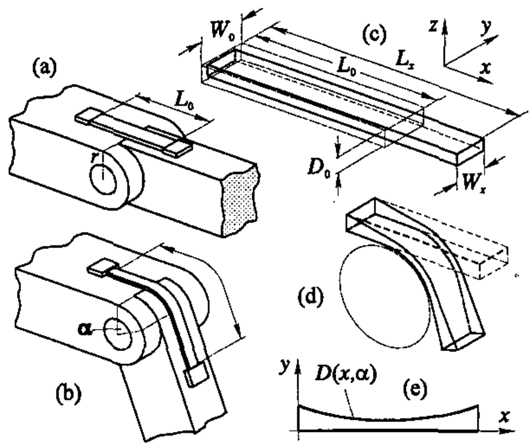

Fig. 3. Schematic presentation of extensive (a,b, c) and compressive (d,e) sensor functioning.

B. *Compressive Sensor*

Attachment of the former sensors onto the joint may result in difficulties. Therefore, we propose compressive sensor, which is, in essence, a variant of capacitive one. It is a sandwich structure with spongy inner layer. Bending of the joint stretches the portion of belt beyond it and presses the sensor strip onto the joint curvature (Fig. 3 (d)) which causes deformation of the spongy layer and hence change of capacity. Relying on equivalent linearized given on picture Fig. 3 (e) we write

$$dC(\alpha) = \varepsilon\frac{W_0 dx}{D(x,\alpha)} \rightarrow C(\alpha) = \varepsilon W_0\int_0^{L_0}\frac{dx}{D(x,\alpha)} \qquad (7)$$

where $D(x,\alpha)$ represents a family of functions describing the profile of compressed dielectric.

All joints do not have the same angle range. Besides, there are certain anatomically-functional correlation between joints of neighbour fingers that decreases the range of independent movements. Therefore, the assigning capability, which includes number of symbols per joint and angle margin, is not the same for all joints.

We should find certain quantity which describes all these aspects.

VI. Functional Capability of Joint

Since we have chosen a particular principle of correspondence symbol/joint angle, that implicitly means the independence of joint bending there is a need to determine the independent range of each joint.

Table I presents maximal angles of particular bending of root (r) and medial (sr) joint of all fingers: (T)humb, (I)ndex finger, (M)iddle, (R)ing and (L)ittle, measured in regard to fully outstretched hand that forms the referent plane. In other words, the actual joint is maximally bent under the condition that all fingers remain outstretched, i.e. remain in their referent position.

TABLE I
JOINT MAXIMAL ANGLES (FINGERS OUTSTRETCHED)

α	T	I	M	R	L
r	31	68	52	60	45
sr	83	110	110	110	100

On the other hand, Table II presents maximum values of joint angles where all other joints were bent freely in order to attain extremal values.

TABLE II
JOINT MAXIMAL ANGLES (FINGERS BENT)

α	T	I	M	R	L
r	31	93	90	86	84
sr	83	110	113	110	104

All measurements were taken by a simple scissors shape tool and carried out over a population of 10 persons, that passed prior short training in order to get proper average results.

The Table III describes correlation between root joints of fingers. The given value of root joint of I finger is measured after following procedure: all fingers are bent backwards and then the I finger in r-joint is bent downwards as much as possible while trying to keep the others in backward position. During such procedure other fingers inevitably move from their starting positions but namely these displacements reflect anatomically-functional relationships between them in the best way.

TABLE III
CORRELATION OF ROOT JOINT: I-FINGER - OTHERS

α[°]	T	I	M	R	L
r	x	75	0	-11	-38
sr	x	/	/	/	/

Of course, the (T)humb, as independent from others, is not included.

If we do the same for all other fingers a Table IV and Table V can be created for root joints

TABLE IV/TABLE V
CORRELATION BETWEEN ROOT JOINTS

α[°]	I	M	R	L
I	75/90	0/25	-11/0	-38/-40
M	0/35	70/85	27/57	-23/11
R	-25/-16	13/40	62/87	-13/50
L	-32/-35	-10/-5	30/40	73/85

with fingers outstretched (Table IV) and bent (Table V) as in Table II.

Finally, the Table VI gives the maximum values of r-joint angles of all fingers being bent backwards

TABLE VI
ANGLES OF ROOT JOINTS BENT BACKWARD

α[°]	T	I	M	R	L
r	0	-33	-21	-19	-28
sr	0	0	0	0	0

The parameter that we seek to describe the joint potential should involve maximal angle range and correlation limitations between fingers, which are significant just for root joints.

From Table I and Table VI the maximum angle range of I-finger r-joint can be determined as

$$\Delta\alpha_{root}^{(I)}\Big|_{\max} = 93^\circ - (-33^\circ) = 126^\circ \tag{8}$$

The correlation between I- and other fingers can be calculated by values from Table IV and Table V, if we notice that it exists only between I and M finger

$$\Delta\beta_{root}^{(IM)} = \frac{(75^\circ - 0) + (90^\circ - 25^\circ)}{2} = 70^\circ \tag{9}$$

It is convenient to normalize these values to get decimal numbers, with the angle of 180 degrees meaning the theoretical limit of joint bending.

The two preceding quantities through mutual weighting produce resultant r-joint parameter I_{root} which we would name f u n c t i o n a l c a p a b i l i t y of joint

$$P\left(I_{root}^{[M]}\right) = \frac{\Delta\alpha_{root}^{(I)}\big|_{\max}}{180^\circ} \cdot \frac{\Delta\beta_{root}^{(IM)}}{180^\circ} = 0.272 \tag{10}$$

Similarly, for r-joint of M-finger we write

$$\Delta\alpha_{root}^{(M)}\Big|_{\max} = 90^\circ - (-21^\circ) = 111^\circ \tag{11}$$

In this case we should cover correlation with both I- and R-finger

$$\Delta\beta_{root}^{(IMR)} = \frac{(70^\circ - 0) + (70^\circ - 27^\circ) + (85^\circ - 35^\circ) + (85^\circ - 57^\circ)}{4} \cong 48^\circ \tag{12}$$

So, we get the value

$$P\left(M_{root}^{[I,R]}\right) = 0.62 \cdot 0.267 = 0.165 \tag{13}$$

In the same manner corresponding values for R- and L-finger can be calculated.

As for middle joints the definition of parameter will be

$$P\left(X_{sr}^{'}\right) = \frac{\Delta\alpha_{sr}^{(X)}\big|_{\max}}{180^\circ}, \quad X = T, I, M, R, L \tag{14}$$

since the correlation between them can be neglected. Parameter values for all joints are given in Table VII

TABLE VII
FUNCTIONAL CAPABILITY OF JOINT

finger	T	I	M	R	L
P_{root}	-	0.272	0.165	0.168	0.15
P_{sr}	0.46	0.61	0.61	0.61	0.57

There an important question arises how to relate symbols and joint angles, whether according to their importance (command or alphanumeric/punctuation keys) or using rate.

VII. REAL GLOVE - VIRTUAL KEYBOARD

Now we face a pure technical question: how to attach all these numerous sensors on joints but not to make the whole device pretty clumsy as in e.g. Scurry?

Therefore, we propose the glove, as a simple integrating substrate, that would associate all these numerous sensors (Fig.4).

How would it work? Just by slipping the gloves onto the hands the gadget is turned-on by a switch that includes internal contacts and (always) wet skin. The power supply depends on whether the device is corded (over cable from PDA) or cordless (battery in the palm-side housing of each glove).

Another important question is correspondence symbol-joint state [10]. Depending of the typing conception, we will consider, among many approaches, the following two:

(a) to assign 3 or 4 or even 5 symbols/commands to each active joint, keeping an acceptable value of the angle margin, (b) to assign almost the whole alphabet to e.g. I, M and R fingers of both hands, leaving other symbols (numerals etc.) to L fingers, and main commands (enter, space, cursor etc.) to thumbs.

In the case (a) the user should "arrange" his joints at proper angles (including margins around it) and keep them temporarily fixed. That causes appearance of corresponding symbols on the screen of PDA, wearable PC display or similar mobile device, which are entered by slight bent of e.g. left thumb middle joint. A condition for such device to enable fast sequential typing is that the user must know assigning rule which means tedious training.

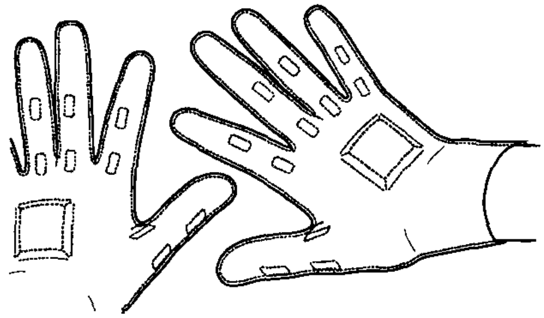

Fig. 4. Virtual keyboard shaped as a glove. Dot rectangles indicate positions of sensors inside the glove fabric wired to processing module situated at the palm top.

In the case (b) the user can scroll the whole alphabet by gradual bending of root and subsequent middle joint of a finger. Therefore, the left-hand R, M, I and right-hand I, M, R fingers cover next six position in the current typing text on the display. Slight bending of thumb joint means start of preparing the next six symbols. Then the user, moving its fingers, scrolls alphabet at each position of desired word at the display and stops corresponding finger as reaches the desired symbol (letter). After all six letters are attained a slight bending of thumb joint follows to enter the symbols - similar to ATM (asynchronous transfer mode). Here is just a question of symbol order per finger: whether the alphabetic one or by letter statistical significance: e-t-a-i-n-o-s-h-r-d-l-u-c-m-f-w-y-g-p-b-v-k-q-j-x-z. [11]

Thumbs and L fingers serve for other symbols and commands. Pointing or mouse function can be fulfilled by changing the activation mode of cursor "keys" from particular to associated one. The cursor/pointing keys/sensors are situated at the thumb root. In its basic mode, as single cursors, the direction key is selected according to thumb movement in one of 4 orthogonal directions, in respect to its neutral/referent position. Of course, there are also margins. But if the pointing mode is selected, all these 4 sensors work as a system, which extensions are integrated into pointer movement across the display. As such, the thumb acts as some kind of joystick.

The glove itself should be made of specific fabric, which would be not so thick, crude, or to much elastic to squeeze the hand or to intolerably disturb finger movements and neutral hand posture. Not to mention comfortable wearing and hand ventilation.

Nevertheless, one may easily conclude that such a gadget needs much practice, as Scurry and Senseboard do, since there is not reference labeling as on classic keyboard, but we claim that it is easy to do so with the accepted principle of considered symbol-key correspondence.

VIII. Conclusion

Miniaturization of hand-held mobile devices resulted in appearance of the concept of virtual keyboard, that reduces the classic typing operation just on hand movement. A couple of prototypes appeared, where each of them relays on finger movement detection by mechanical or optical sensors, assigning particular symbolic value to corresponding hand posture, i.e. finger disposition. Such process, where the temporal hand postures are recognized as intended symbols, is inevitably accompanied by uncertainty and errors, needs extensive training and precision. Also these devices assumes very complex sensors. Apart from user-friendly difficulties and ergonomic clumsiness the chief shortcoming is namely a pair of additional "mobile" devices which should accompany the basic one - PDA or WearPC. Nevertheless, our proposal of virtual keyboard keeps track of such concept but introduces several improvements in relation to existing ones - Senseboard and Scurry. As first, we have chosen rather particular correspondence 'finger movement - typed symbol', which means independent and separate selection. In addition, the use of very simple extension sensors makes it more reliable and simple for exploitation. Although we didn't managed to overcome the two more mobile devices, having associated numerous sensors into gloves one could consider them not as a gadget but rather a fashion detail, produced in many appearances and sizes, where nobody will "notice" that they hide a keyboard.

This is, at last, the main objection to such a concept - three instead of one mobile devices. So we do not see this concept as final and the only perspective for research direction of virtual keyboards.

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