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Exploring tilting methods for typing under water

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Abstract

Underwater environments are still providing significant challenges for diver communication and interaction. Smartphones and tablets have the potential to provide great assistance for divers under water and even allow them to utilize augmented and mixed reality, but the housing solutions limit their capabilities. In particular, interaction with them cannot harness a touch screen medium. This paper presents a novel way of providing textual input in underwater environments. The concept is utilizing orientation sensors allowing for tilting a smartphone to input textual information. Three different titling configurations of keyboards were implemented and evaluated on land and in a swimming pool in a user study that involved 17 healthy volunteers and assessed their performance in two different conditions reflecting two typical diving poses. Results clearly demonstrate the benefit of this technique and suggest more effective configurations. A following discussion derives general recommendations for implementing similar methods that use tilting to interact with devices under water.

Keywords Underwater interaction · Typing · Keyboard · Tilting · User study

1 Introduction

Underwater environments are considered hostile territories for humans with specific challenges such as high pressure, corrosion, and signal processing issues related to data transmission and sensing [23]. They are also characterized by non-uniform lighting and poor visibility, due to scattering and absorption [26]. Even though there are some expensive systems for diver communication, mainly used by the military and oil industry, the majority of divers use hand signals [5]. Written communication and signing are relatively slow

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and restricted by diving equipment [12], and the typical medium is rigid plastic underwater slates.

The availability of mobile devices underwater is becoming more and more common due to advances in waterproof housings. Apart from recreation diving, which is on the rise over the past years, there are several application domains, such as monitoring, disaster, military, navigation, and sports, where divers perform various tasks [8]. To complete them, they require to navigate through the area, see a description of individual steps of a given task, and note their findings in the form of simple words or options selected from a list of predefined choices. In recent years, divers can also see virtual objects under water and exploit the benefits of augmented reality (AR) [3].

To our knowledge and personal experience, existing commercial waterproof housings do not allow for constructive interaction. For example, one device [14] uses a hard plastic with anti-pressure sensors, but mobile screen interaction is not practical. The precision of touch is very low due to the presence of an extra flexible membrane and due to gloves protecting the diver's hands, so the user interface requires large buttons to compensate this lack of precision. The cover also disallows using swipe gestures. Another type of housing [7] utilize a small set of Bluetooth buttons, but the touchscreen of the devices is entirely unavailable. Typing with techniques adapted for a low number of keys [17] is extremely slow and cumbersome. A specialized hardware, such as an external underwater keyboard, is also not an option, since divers usually cannot operate more than one device at a time, for practical and safety reasons.

This paper addresses the problem of interacting with smartphones by divers under water, especially the problem of typing or selecting answers from several options. It is inspired by techniques utilizing tilting as input that were tested on land, but their usage for underwater interaction is still an unexplored area. Various techniques have a different number of degrees of freedom (DOF) and a different number of steps required to write a single letter. The paper proposes an experiment to evaluate three types of keyboards (a 2-DOF keyboard, a 1-DOF keyboard, and a two-step 1-DOF keyboard) controlled by tilting the device, which is transferred to a selection of keyboard button.

The main contribution of this research is an effective solution for underwater text inputting. In particular, the paper introduces three fundamental methods of using tilting as a method of selecting objects from a list of options. Each method is represented with a dedicated keyboard selecting a letter from the alphabet and assessed in a user study performed with 17 healthy participants in a swimming pool. Additionally, another study is conducted with participants doing the same experiment on land to compare the techniques with similar state-of-the-art methods intended for usage outside of water.

The performance of the three keyboards is evaluated in two basic postures reflecting divers standing stable of the bottom and swimming in water without any support. The evaluation operates with the number of misclicks, the speed of writing, the time spent with aiming at the buttons before clicking, and the personal opinion of the participants. Finally, the results are generalized to identify the advantages and disadvantages of each method and provide recommendations on choosing the best solution for various tasks performed under water.

The rest of the paper is structured as follows. After presenting a background with the relevant work in Section 2 and 3 describes the methodology of the experiment, including the hardware and software, the three keyboards, the testing procedure, and the evaluation. This is followed by measured results in Section 4 and a discussion in Section 5. Finally, Section 6 concludes the whole paper.

2 Background

The interaction of divers with mobile devices is very complicated under water. Bellarbi et al. [1] designed an AR system for swimmers and used joysticks and buttons to control it. Oppermann et al. [21] presented another AR system that used a tablet in a waterproof housing with a conductive layer to support touch that allowed swimmers to access it; however, this solution was designed only for small depths of swimming pools.

The area of more sophisticated interaction between divers under water and mobile devices is still quite unexplored, especially in the field of techniques for writing texts. DeMarco et al. [6] discussed various methods for communication between divers and autonomous underwater vehicles or robots in typical use case scenarios. They evaluated them with an experiment, in which the recognition and processing functions of the robots were performed by humans remotely operating the robots. Menix et al. [18] focused on the detection and recognition of diver sign language and presented a method based on Markov chains to identify eight basic diver gestures. Mital et al. [19] also worked on understanding diver sign language and built a solution based on neural networks and eight Hu image moments. Chiarella et al. [4] designed a specialized sign language for communication between divers and robots under water that was easy to recognize and allowed the divers to give various orders to the robots. These solutions are extremely elaborated and still allow only selecting an option from a list of predefined choices.

The possibility of utilizing accelerometers and gyroscopes to control devices using tilting is discussed a lot in the last two decades since Rekimoto [25] presented an idea of tilting a device to choose an item from a list (1-DOF manipulation) or to navigate on a map (2-DOF manipulation). Partridge et al. [22] presented hardware similar to wristwatch consisting of four mechanical buttons that recognized tilting in eight basic directions, which allowed the wearers to write simple texts. Wigdor et al. [30] added tilting to a 12-button keyboard of mobile devices of those days, which increased the speed of writing.

Moreover, Rahman et al. [24] analyzed a design of techniques that used tilting of a wrist with a focus on the range of possible motions, discretization of the space, selection mechanism, and visual or other feedback. Jones et al. [15] designed and compared several keyboards that were controlled by moving and tilting Wii controllers, and decreased the number of motions to distinguish at the cost of introducing several steps to select a single letter. Ljubic et al. [16] reduced the number of identifiable tilted orientations to four and introduced a keyboard that required five steps to write a letter. Hong et al. [13] focused on small screens of smart wristwatches and designed a keyboard composed of two halves of the standard QWERTY keyboard that were switched by swiping. Oney et al. [20] introduced a concept of a keyboard that zooms its parts that are clicked by the user until the clicked key is accurately chosen, and presents the benefits of these keyboards in extremely small screens.

Furthermore, Walmsley et al. [29] focused on 1-DOF keyboards and used predictions, autocorrection, and optimized keyboard layout to allow writing words without any pressing, only by using gestures similar to swiping on regular touchscreen keyboards. They also introduced additional gestures for commands like Space, Backspace, or to confirm a completed word. Gong et al. [10] designed a keyboard with an optimized layout of letters controlled by tilting wrist. They optimized the distribution of keys and incorporated autocompletion to reduce the number of options to choose from when writing.

In another study, Yeo et al. [31] introduced an idea of using tilting to control a cursor on the screen and used a swipe keyboard to write a text. Gupta et al. [11] worked further on this idea and developed specialized ring-like hardware that tracked the tilting of the hand

and palm in various body postures. They also used tilting to write a text with a swipe keyboard. Fitton et al. [9] examined the influence of the user's movement when walking on his or her ability to write text by tilting the device. Castellucci et al. presented TiltWriter [2], a method for inputting texts solely by using tilting without any need for buttons. They applied their technique to keyboards with the standard QWERTY layout and with a customized layout and tested them with sitting participants. These methods were not tested in underwater environments, so their performance and limitations in such conditions are unknown.

3 Methodology

3.1 Hardware and software

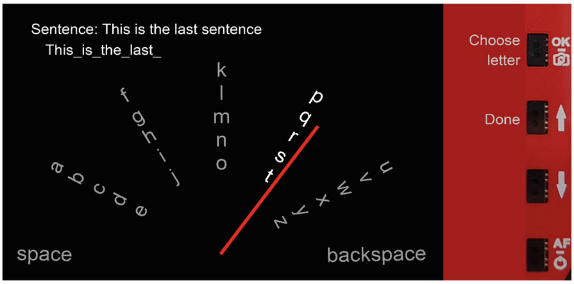
The system was developed in Visual Studio 2017 in C++ as a native-activity application and deployed on a Samsung S8 smartphone with 64 GB of internal memory and the Android 7.0 operating system. The rendering was performed by the OpenGL ES 3.2 library.

The smartphone was sealed in a Diveshot housing from Easydive [7], see Fig. 1a. This housing completely covers the smartphone and prevents divers from accessing its screen. It uses Bluetooth for communication and controls the smartphone with five optical buttons located at the right part of the housing. They are pressed by covering a corresponding sensor

a

Samsung S8 sealed in Diveshot, a waterproof housing from Easydive. The smartphone cannot be accessed directly by divers and is controlled by five optical buttons in the right part of the housing. The participants operate the lower four buttons that correspond to the four buttons of the application. The fifth, top-most button is used by the supervisor to access and change the experiment's settings.

b



Screenshot of the application when a participant writes a sentence. The description of buttons occupies the right part of the screen, the upper part is composed of the sentence to write and a line with a written text, and the lower-left part contains the keyboard with an arrow indicating the current device orientation and a highlight of an active group of letters.

Fig. 1 **a** Smartphone sealed in a waterproof housing; **b** screenshot of the application during a test with a thumb and recognize a long press when the diver holds the finger over the sensor for several seconds. The housing also contains a window on its back that allows the smartphone to take pictures and videos; this feature was not utilized during testing since there was no use for the camera.

Each button of the housing has a different function based on the current state of the application. The right part of the screen contains an illustration of the lower four buttons, whose position corresponds to the housing buttons. A label located next to each button describes its current functionality in the application. The last fifth button localized above the four buttons did not have any function for the user during the test, but it allowed the supervisor to change the experiment's settings when pressed for a few seconds. However, this functionality was hidden to the participants.

During development, it found that it is optimal to assign the *Choose letter* function to one button, and the *Next step* (or *Done*) and the *Previous step* (or *Back*) functions to different two buttons. Although some on these functions could be combined to decrease the number of buttons required by the application and increase the number of buttons available for operating the keyboards, such combination would lead to a complicated interface and confusion among the users. For this reason, all keyboards are operated with only a single button.

The screen of the application was divided into three parts, see Fig. 1b. The right part (about 23 % of the screen) contained the description of the four buttons available to the user and included an illustration of the corresponding buttons. The top part of the screen (about 20 % of the screen) was composed of two lines, one with a sentence to write and the other one with a written text, and the keyboard occupied the rest of the screen. A participant operating the smartphone under water and all keyboards in action can be found in a supplementary video.

3.2 Selecting objects by tilting

Participants tested three different ways of tilting as methods to select letters of the alphabet to type a sentence. The absolute orientation of the device is derived from the direction of the gravity vector measured by the accelerometer. Its value affected the position of the selector directly, since this solution provides better results than using the orientation as a selector's velocity [28].

The first method tilts the device in two directions (two degrees of freedom) and transforms the orientation of the device to a position of a dot on the screen that selects letters. This method is called QWERTY because it uses the same layout of keys as standard computer keyboards (see Fig. 2a).

The second method tilts the device in just one direction and transforms its orientation to an angle of an arrow that selects a letter from letters ordered alphabetically. This method is called Fan (see Fig. 2b) since the user selects a letter from a fan of options. More sophisticated distributions of letters [29] were not considered, because people are not familiar with them, which can lead to confusion and requires an additional training phase.

The third method is called Fan2, and it is a variation of the Fan keyboard, which uses two steps to select a letter: first, the user selects a group of letters (see Fig. 2c), and then the user selects a letter from that group (see Fig. 2d). Thanks to this, the virtual buttons of this keyboard are larger than those of the Fan keyboard, making them easier to select at the cost of needing two clicks to write a single letter. In addition to letters, all three keyboards also have the Space and Backspace keys to add a space and remove a letter, and the Fan2 keyboard has a Back key to leave a selected group of letters to choose a different one.

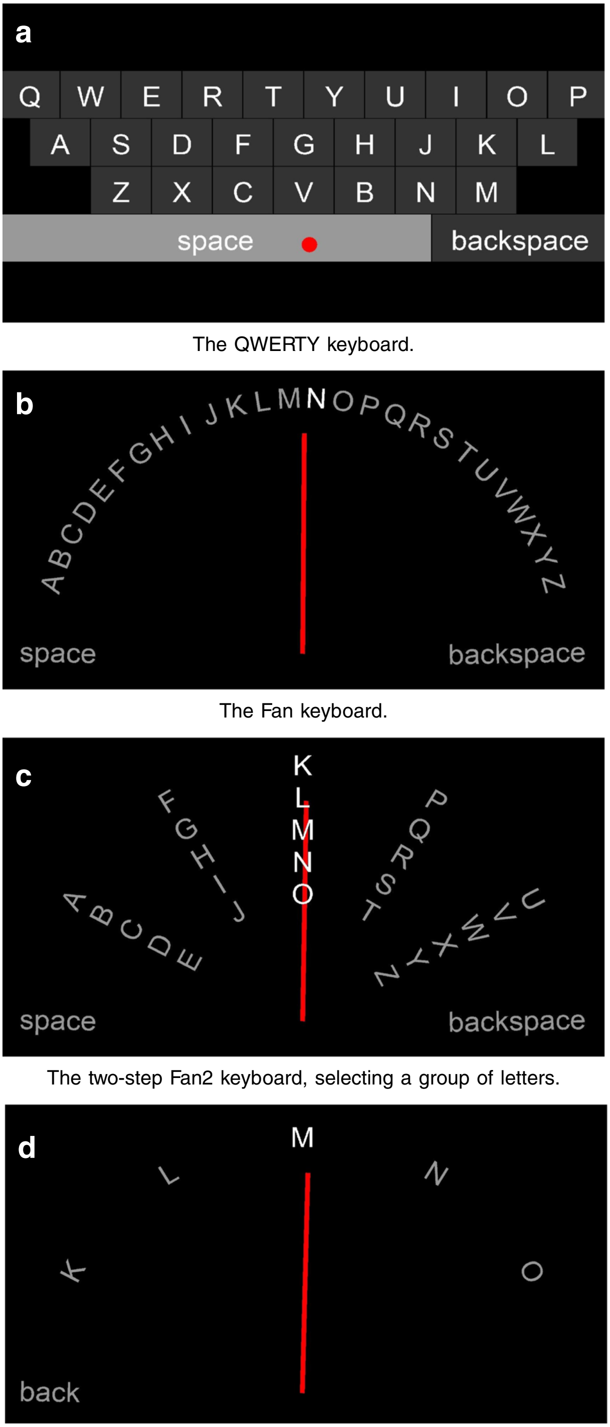


Fig. 2 The three evaluated keyboards: **a** QWERTY, **b** Fan, **c**,**d** Fan2

A particular key is selected by tilting a device and pressing a button of the housing. The position of the dot or the arrow is derived from the direction of the gravity measured by the smartphone accelerometer and clamped to the region of the keyboard. This clamping simplifies the selection of keys at its edges, as was observed during the development. In case of the QWERTY keyboard, it is easier for users to tilt up to select letters from the top row, tilt down to select Space or Backspace, tilt left to select Q or Space, and tilt right to select P or Backspace – the keys in the corners (Q, P, Space, and Backspace) are notably easier to hit than others since they required the least amount of aiming. In the case of the Fan and Fan2 keyboards, the keys that are easy to choose are the keys at the two ends of the fan: the Space key, the Backspace key, and the Back key.

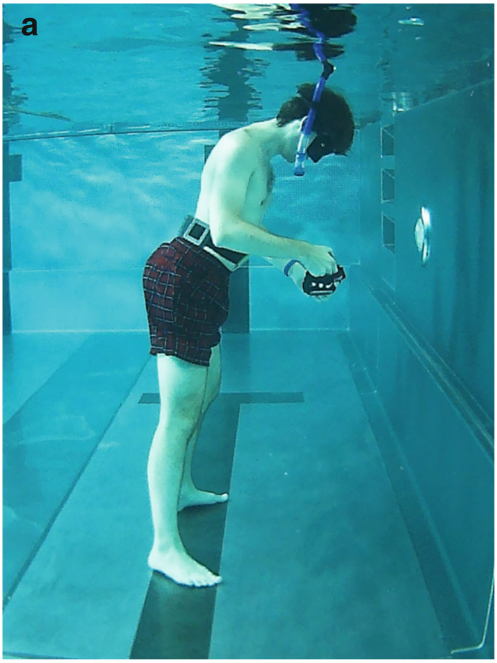
Each keyboard has a different range of operations and different angle of directions that correspond to specific keys. In the case of the QWERTY keyboard, each letter key spans the angle of 4.44 degrees in the left-right range, and each row spans the angle of 7.16 degrees in the bottom-top range. The full range of operation of the QWERTY keyboard is thus 44.4 degrees in the left-right direction and 28.6 degrees in the bottom-top direction. In the case of the Fan keyboard, each letter spans the angle of 2.38 degrees per letter, and Space and Backspace keys are larger and span 6.87 degrees. The full range of this whole keyboard is 77.4 degrees. The Fan2 keyboard contains fewer keys and thus can be more compact, each letter and group of letter spans 7.73 degrees, and Space, Backspace, and Back keys span 4.3 degrees. The full range of operations is 48.7 degrees. These ranges were obtained in a preliminary test, which showed that the Fan keyboard requires a considerable span to allow the users to select individual letters. On the other hand, a similarly broad span applied to the Fan2 keyboard required the users to do unnecessarily large movements with the device, so its span was reduced.

Each keyboard has its advantages and disadvantages. The QWERTY keyboard uses two degrees of freedom, which allows the keys to span a larger area and be more comfortable to hit. However, the users must focus on balancing the keyboard in two directions instead of only one when compared to the Fan and Fan2 keyboards. Moreover, while it is easy to choose the central position of the dot in the left-right direction, the central position in the bottom-top direction depends on a posture in which the divers operate the keyboard: keyboards that are operated with their screen directed vertically are nearly impossible to use when the screen is horizontal and vice versa. The Fan keyboard uses only one degree of freedom, so the users can focus on only one direction when aiming for the key, but the keys have the lowest span of angles and thus are hardest to hit. The Fan2 keyboard benefits from positives of the other keyboards, it uses only one degree of freedom, and its letters span the larges range of angles, but it requires the user to make two clicks to write a single letter (first to choose a group, and then to choose the letter), which decreases the speed of writing.

3.3 Testing site and postures

An early version of the Fan keyboard was a part of an AR application, which was tested by eight professional scuba divers in the Mediterranean Sea [3]. Their task was to observe virtual objects, and then input their name and answer questions about their underwater experience at a depth of 5 meters. Informal feedback showed enthusiasm through the divers, mainly because that it was the first time that in their experience that they could input textual information in underwater environments. They all agreed that the concept of inputting text by tilting is solving many issues; however, they also reported problems with hitting the letters and varying performance of writing when they swam or stood on the bottom.

Fig. 3 Two postures of participants: **a** standing on the bottom, **b** floating on the water



A participant standing on the bottom, wearing a belt with 4 kg weight to help him sink to the bottom and avoid rising to the surface.

A participant floating on the water, having a pull buoy below his belly to help him float on the water.

To better assess the strengths and weaknesses of the Fan keyboard and other configurations and to find the optimal solution, we conducted another user study focused only on writing with more (although non-expert) users in a controlled environment. This study was performed by 17 participants in a swimming pool of depth of 1.75 meters in a swimming lane reserved for testing. To capture the difference in the performance of divers, users performed the study in two postures: standing on the bottom of the pool (see Fig. 3a), and floating on the water (see Fig. 3b). They got a diving mask and a snorkel to see and breathe under water and a 4 kg weight to sink to the bottom or a pull buoy to float with ease on the water. To ensure their safety, participants performed the test at the edge of the swimming pool and they under the constant supervision of a person directing the study. The supervisor also watched the participants and adjusted their position if they moved away, especially when they floated on the water.

An additional test was performed by another group of 17 participants on land to obtain results comparable with other methods designed for typing on land. The device was still in the waterproof housing, even though they did the test outside of water. The participants tested the keyboard when standing on their feet.

3.4 Procedure

Participants that tested the keyboards in the swimming pool attended a single testing session, which took about two hours in total. Before the session, they received the details about the testing and got familiar with sentences and the questionnaire. The testing sessions started with an introduction, in which they signed the informed consent and learned about the equipment and the hardware. They were instructed to familiarize themselves with all three types of keyboards by writing *Hello world* phrase. In the case of the QWERTY keyboard, the participants could choose from two layouts, QWERTY and QWERTZ (a popular layout in Central European countries). The central position in the bottom-top direction was set for participants floating on the water; they were instructed to bend during the introduction and standing on the bottom so that the device was directed similarly.

The testing consisted of six stages. In each stage, participants wrote one sentence; in the first three stages, they were standing on the bottom of the pool, and in the other three stages, they were floating on the water. All participants were first standing on the bottom and then floating on the water, as the divers from the preliminary test reported that the manipulation is more comfortable when they touched the bottom and were stable. The participants worked with different keyboards in each stage, and to prevent the results from being affected by the fact that individuals can transfer their skill from one keyboard to another (most importantly between Fan and Fan2 keyboards), the order in which they used the keyboards was randomized. They used the same order of keyboards when standing and floating.

The participants were asked to write the following six simple sentences: “The weather is nice today”, “The test is done in a pool”, “The water is very clear”, “This is the fourth stage”, “The user is floating on water”, and “This is the last sentence”. The sentences were known to participants in advance, and they were shown on the screen. The order of the sentences was the same for all participants.

After participants finished each stage, they filled a questionnaire to obtain their personal opinion on using the corresponding keyboard in the corresponding posture. The following six questions, chosen from a validated questionnaire by Tcha-Tokey et al. [27], were provided to them:

- *Concentrate*: I could concentrate on the assigned tasks rather than on the controllers.
- *Control*: I felt I could perfectly control my actions.
- *Nervous*: I felt nervous during my interaction with the controllers.
- *Skillful*: It would be easy for me to become skillful at using the controllers.
- *Learning*: Learning to operate the controllers would be easy for me.
- *Practical*: Personally, I would say the controllers are practical.

This questionnaire asks the participants to provide feedback using a 7-point scale, ranging from *Not a all* (1), past *Somewhat* (4), to *Completely* (7). Filling the questionnaire also served as a relaxing part for them to calm and got ready for the next stage. They did the test in pairs; when one was writing a sentence, the other was filling the questionnaire.

As a reward, participants were allowed to use the rest of the reserved lane for swimming, and they could also come for swimming outside of their testing sessions. At the end of the session, after finishing all six stages, which took from 40 minutes to one hour, they filled their personal information and provided the qualitative feedback on the whole study.

The experiment performed on land was done similarly. Participants received the details about the testing in advance, and the session started with the same introduction. The test itself was smaller and consisted of only three stages in which they stood in a similar pose as those standing on the bottom of the pool. They filled the questionnaires about each keyboard at the end of each stage. The end of the session was the same; they filled their personal information and provided qualitative feedback. The whole session was shorter and took about 30 minutes to complete. The participants were tested individually in an empty room with a supervisor and received a small gift after the testing.

The evaluation in the swimming pool was done by 17 participants, nine females and eight males. Six participants were 18–25 years old, nine were 26–33 years old, and two were 34–41 years old. All participants used the right hand as their dominant hand, were familiar with smartphones, and used them on a daily basis (in the range from 1 – *Not at all* to 5 – *Very much*, their average use of smartphones was 4.18 with a standard deviation of 0.95). Two participants required their weight to be increased by 4 kg to a total of 8 kg to be kept under water. Three participants used QWERTZ layout of the QWERTY keyboard.

The evaluation on land was also done by 17 participants, six females and eleven males. Nine participants were 18–25 years old, and eight were 26–33 years old. Fifteen participants used the right hand as their dominant hand, and all of them were familiar with smartphones as well (their average use of smartphones was 4.35 with a standard deviation of 0.68). Five participants used QWERTZ layout of the QWERTY keyboard.

3.5 Evaluation

In addition to the questionnaires gathering personal opinions of the participants, the keyboards were compared according to the number of misclicks that participants did, the average time required to write a letter, and the time spent on aiming at a key before it was pressed. The application logged the presses of buttons and the position of the selecting dot or arrow, together with the timestamp of these events.

Every click that the application recorded was divided into one of the following categories:

- A click that was correct and intended to do. The time per letter and the time spent with aiming are recorded.
- A misclick that the user did not intend and accidentally clicked on an adjacent key. The time per letter is recorded, but the aiming time is not. The number of misclicks is increased.
- A click that represents the first click after the test started. The average time is not recorded, because the user spent some extra time with familiarizing with the task, e.g., with reading a sentence to write. The aiming time is recorded.
- A click that is the first click and also a misclick. No time is recorded, but the number of misclicks is increased.
- An erroneous click that happened when the user accidentally pressed the housing button and chose a key. Aiming times and average times per letter are not recorded, and also the number of misclicks remains the same.

On very rare occasions, water accidentally got into the snorkel, and the experiment was briefly paused. When it continued, the data about the first following click were ignored.

In addition to the average time per key, which is computed as the sum of times between pressing valid keys divided by the number of these valid keys, the evaluation is also based on the average time per letter. It is the same sum divided by the number of valid letters (including spaces), and the average number of words written per minute, where one word is a sequence of five letters or spaces [2]. The average time per letter is particularly important for the Fan2 keyboard, which requires to press two keys to write a single letter. The aiming time is based on a time that elapses between the first event when the pressed key is focused on the selecting dot or arrow before it is selected and the moment when the key is pressed.

The results were compared using the independent unpaired t-test to find whether the difference between results is statistically significant.

4 Results

The feedback of the participants on individual keyboards is in Fig. 4. It shows promising results of the Fan2 keyboard in all tested suspects, of the QWERTY keyboard when participants floated on the water, and of the Fan keyboard when participants stood on the bottom.

Statistics of individual presses are in Table 1. This table shows that the Fan2 keyboard required the highest number of clicks as a consequence of needing two clicks to write a single letter. It also achieved the lowest number of misclicks, unlike the Fan keyboard with the highest number. Users did more misclicks when floating on the water than when standing on the ground, although in the case of the Fan2 keyboard, the difference is much lower than in the case of the other two keyboards. In tests performed on land, the number of misclicks is very low compared to tests performed in water, thanks to a more stable environment. The number of misclicks of the Fan keyboard is higher even on land because the keys are smaller than those of the other keyboards.

Table 1 The number of intended clicks, misclicks, erroneous clicks, correctly written letters (including spaces), the number of corrections (backspaces and presses on *Back*), and the average speed of writing measured in words per minute (WPM). The percentages of intended clicks, misclicks, and erroneous clicks are derived from the number of all clicks; the percentages of written letters and corrections are derived from the number of all selections (i.e., letters, spaces, backspaces, and presses on *Back*)

Keyboard	Posture	Intended clicks	Misclicks	Erroneous clicks	Correct letters	Corrections	WPM
QWERTY	Standing	489 (86.2 %)	77 (13.6 %)	1 (0.2 %)	414 (84.7 %)	75 (15.3 %)	2.04
QWERTY	Floating	557 (83.9 %)	105 (15.8 %)	2 (0.3 %)	448 (80.4 %)	109 (19.6 %)	2.31
QWERTY	On land	435 (95.6 %)	19 (4.2 %)	1 (0.2 %)	416 (95.6 %)	19 (4.4 %)	4.15
Fan	Standing	561 (81.4 %)	125 (18.2 %)	3 (0.4 %)	427 (76.1 %)	134 (23.9 %)	2.16
Fan	Floating	653 (76.3 %)	198 (23.1 %)	5 (0.6 %)	448 (68.6 %)	205 (31.4 %)	1.78
Fan	On land	483 (90.4 %)	49 (9.2 %)	2 (0.4 %)	428 (88.6 %)	55 (11.4 %)	3.34
Fan2	Standing	873 (95.3 %)	35 (3.8 %)	8 (0.9 %)	427 (88.4 %)	56 (11.6 %)	2.47
Fan2	Floating	888 (95.8 %)	39 (4.2 %)	0 (0.0 %)	437 (90.5 %)	46 (9.5 %)	2.63
Fan2	On land	806 (97.8 %)	17 (2.1 %)	1 (0.1 %)	414 (94.5 %)	24 (5.5 %)	2.77

Speeds of clicking on keys and writing letters, with and without adjustments reflecting making misclicks, and times of aiming at buttons in the central parts of the keyboards and the edges are in Fig. 5. The time required to do a click is lowest in the case of the Fan2 keyboard, which relates to the fact that this keyboard has the broadest range of angle per key. However, since this keyboard requires two clicks to write a letter, the time per click is less important than the time required to write a letter. When not adjusted to misclicks, this time of the QWERTY and Fan keyboards is lower, but since the users made many mistakes with these keyboards, the time is lowest in the case of the Fan2 keyboard after adjustments to these errors. The aiming times of the Fan2 keyboard are similar for both the central keys as well as for keys at the edge. In the case of the Fan keyboard, aiming times of the keys at the center are higher than those of keys at the edge, which is also true for the QWERTY keyboard when users floated on the water. In the case of the QWERTY keyboard and participants standing on the bottom, the aiming times are high for the central buttons as well as for the Space and Backspace buttons at the edge.

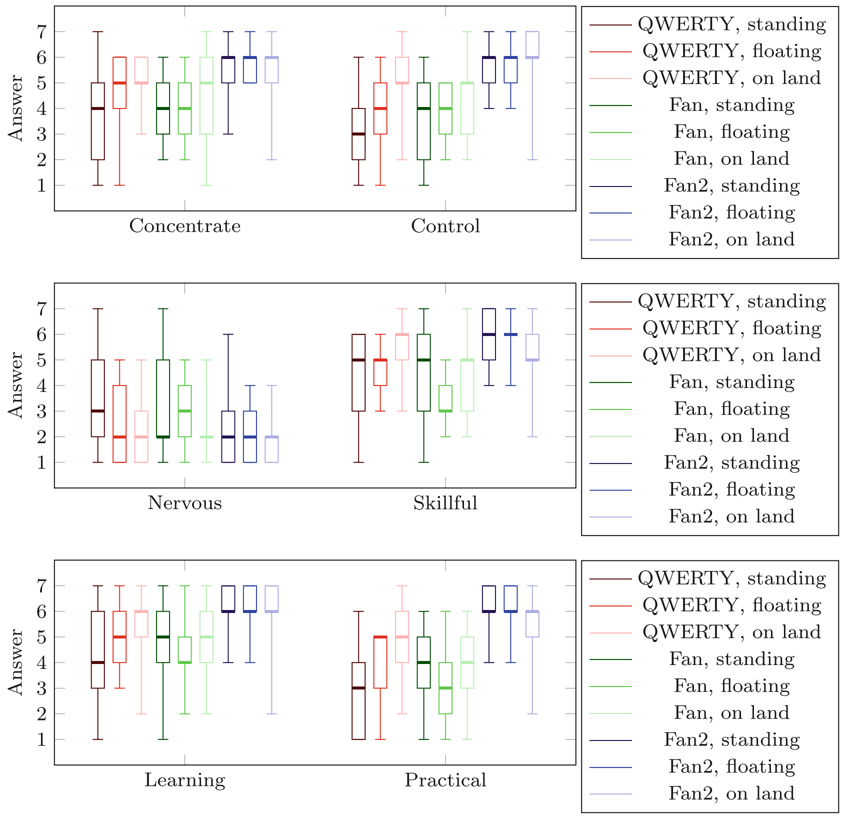


Fig. 4 Feedback of the participants on using individual keyboards in all tested postures. Possible answers were ranging from 1 – *Not at all*, pass 4 – *Somewhat*, to 7 – *Completely*. Questions are: *Concentrate*: I could concentrate on the assigned tasks rather than on the controllers; *Control*: I felt I could perfectly control my actions; *Nervous*: I felt nervous during my interaction with the controllers; *Skillful*: It would be easy for me to become skillful at using the controllers; *Learning*: Learning to operate the controllers would be easy for me; *Practical*: Personally, I would say the controllers are practical

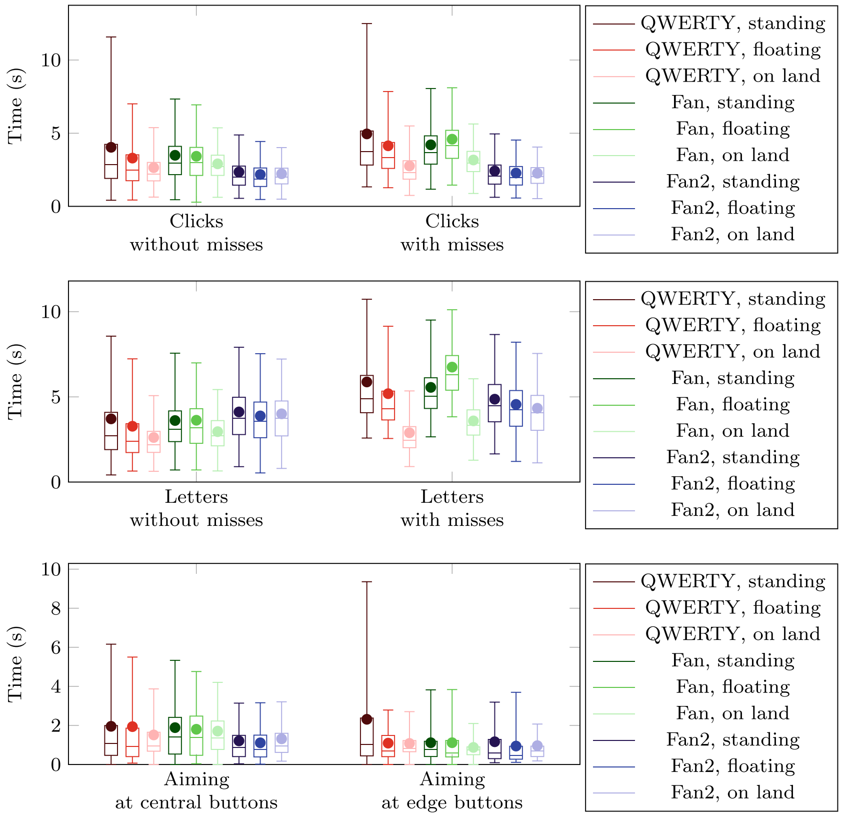


Fig. 5 Times (in seconds) required to click on a key and to write a letter, without and with adjustments reflecting making misclicks, and times (in seconds) spend with aiming at buttons in the central part of the keyboard (letters) and the edge of the keyboard (Space, Backspace, Back). Percentiles are 0, 25, 50, 75, and 95; percentile 100 (maximum) is not present to avoid spikes. The full dot represents the average value

Tests performed on land showed that the speed of clicking on buttons of the QWERTY and Fan keyboards is much higher, and they even outperform the Fan2 keyboard. The number of words written per minute (WPM), presented in Table 1, confirms that the speed of writing in water is the highest with the Fan2 keyboard, even though writing with this keyboard is the slowest option on land.

4.1 Feedback

The main feedback was related to the hardware buttons of the housing. When tested on land, the buttons reacted on fingers at greater distances, so the fingers had to be moved farther for the housing to recognize different press. This range was much less under water, which made operating the device more natural, as was noted by two participants. Three participants complained that the range was still too high. One participant mentioned that the optical sensors were also too sensitive and recognized a press when it was not intended, but on the other hand, two participants declared the opposite.

Two participants would prefer mechanical buttons for a faster localization of buttons and more reliable pressing, and one participant suggested using some grooves to find the buttons by touch. Four participants mentioned their visual attention was split between following the arrow or the dot on the screen, and searching for the optical sensor to press. One participant was confused by the correspondence between four buttons on the screen and five buttons of the housing.

One participant explicitly stated that the writing was more comfortable when standing on the bottom of the pool, but one participant stated the opposite. Five participants complained that writing was very hard due to other swimmers swimming in the adjacent lane. Several participants admitted they knowingly left several mistakes in the written text, usually when testing a keyboard that they did not like, and when they did not notice the error before typing more letters.

All participants agreed that the Fan2 keyboard was the keyboard they liked the most. The least popular keyboard was the QWERTY keyboard, as stated by three participants, and the Fan keyboard, as stated by one participant. One participant mentioned that the sensitivity of the Fan keyboard was too high and that it was very hard to select a letter, but one participant stated the opposite, saying that the sensitivity was too low and it was hard to reach the edges of it. Several participants stated that it was hard to reach the Space and Backspace keys of the QWERTY keyboard when they stood on the ground. Some also stated that these keys were not visible when the device was tilted or the rim of the housing hid them. One participant appreciated the familiarity of the QWERTY keyboard layout. Four participants stated that the dot and the arrow were moving in the opposite direction than they expected.

Three participants explicitly stated that they enjoyed the experiment and that they had a great time.

Supervisor observed that although all participants were explicitly told to bend and keep the device below their eyes when standing on the ground, many participants did not do so, which complicated writing with the QWERTY keyboard.

The feedback taken from participants doing the experiment on land showed that the main issue was again the sensitivity of the button. The participants had to perform extensive movements to get out of the reach of the optical sensors and often tried to press the button several times before the press was recognized. Ten users explicitly stated problems with pressing the buttons, and a few more participants mentioned this issue orally. One participant started using a swiping movement to press the button, describing it as more reliable and straightforward to perform automatically.

Five participants found the Fan2 keyboard as the best option for writing, although two participants mentioned having problems with finding the required group of letters with buttons, and one participant described it as the worst option given the problems with pressing the buttons. One participant found the QWERTY keyboard as the best. One participant mentioned difficulties with reaching the edged of the Fan keyboard. Two people expected the selector to move in the opposite direction when tilted, and one person expected the tilting to affect the selector's velocity instead of its position. One participant would appreciate the selector to snap to the keys. Three participants found the housing very heavy.

5 Discussion

The results show a statistically significant difference between many aspects of the Fan2 keyboard when compared to the other two keyboards. The results of the personal opinion of divers show that the Fan2 keyboard is better than the QWERTY keyboard or the Fan keyboard regarding their ability to concentrate during the task ($p < 0.01$), to control their actions ($p < 0.001$), becoming skillful at using the device ($p < 0.01$), to learn to operate the device ($p < 0.05$), and their opinion that the controllers are practical ($p < 0.001$). Also, it is better concerning the time of click ($p < 0.001$), the time of aiming at the central buttons ($p < 0.001$), and the time of writing letters when adjusted with mistakes ($p < 0.01$), even though it requires two presses to write a single letter.

In the case of the users standing on the bottom, the Fan keyboard was better than the QWERTY keyboard in the time of clicking ($p < 0.02$). This was most probably caused by the fact that despite instructions, the QWERTY keyboard was operated in front of the participant and not below their heads, which complicated the manipulation with the keyboard. This is also supported by the fact that when floating on water, the QWERTY keyboard provided better results than the Fan keyboard in times for clicking and for writing letters adjusted with mistakes ($p < 0.05$) because the device was below participants' heads. The Fan keyboard contained the highest number of misclicks, which correlates with the fact that the keys spanned over the lowest angle, and thus it was harder to precisely hit the key.

The aiming times confirm these statements. The times of the Fan2 keyboard are low both in the center and at the edge, which corresponds with the fact that the keys were bigger, and thus it was easy to hit them. The fact that the times are very similar for the keys in the center and keys at the edge indicates that the aiming was not the issue in this case, and other issues like finding and pressing the correct button to click were more common. The aiming times of the Fan keyboard showed that it was much easier to hit the keys at the edge ($p < 0.001$), most probably due to their larger size and the fact that the arrow was clamped and could not go outside of the range of the keyboard, so the users could overshoot the range and still click the correct key. Aiming times of the QWERTY keyboard indicate problems with pressing Space and Backspace keys when the participants were standing on the bottom of the pool.

Results indicate that in case of the QWERTY keyboard, participants that floated on the water could concentrate better ($p < 0.22$), could control it better ($p < 0.19$), felt less nervous ($p < 0.18$), could learn better to operate it ($p < 0.23$), and found it more practical ($p < 0.06$) when compared to standing on the bottom. However, the p value is high, which makes these results not statistically significant. Similarly, regarding the Fan keyboard, participants that floated on the water felt it would be harder for them to become skillful with this keyboard ($p < 0.06$), and found it less practical ($p < 0.1$), but the value of p is again too high.

The tests performed on land clearly show that clicking on keys of the Fan2 keyboard is faster than on the QWERTY keyboard ($p < 0.001$), which is faster than on the Fan keyboard ($p < 0.01$). This cannot compensate for the necessity of requiring two presses to write a letter, which makes the Fan2 keyboard the slowest option for writing on land ($p < 0.001$). Despite this, it was still rated high in user feedback. The times spend on keys before being selected confirm the observed problems with pressing the buttons on land.

The user study showed the necessity of a correctly set center in one degree of freedom of the QWERTY keyboard, which complicates its usage in real scenarios, as the posture in which the keyboard is used is not constant and changes. For real-world usage, the participants' feedback also suggests personalizing the keyboard in the mean of arrow sensitivity and tilting direction. It also suggested some improvements to the hardware regarding the construction of buttons.

The fact that the number of corrections in Section 1 differs from the number of misclicks has several explanations. The number of corrections includes corrects of a small number of clicks done by accident (erroneous clicks), which increases its value. Users also did not correct several misclicks and erroneous clicks, which decreases the number of corrections, but on the other hand, some users were willing to clear several correct letters to correct a mistake they noticed after they wrote those correct letters.

Current methods for on-land writing by tilting [10, 11, 31] report much higher speeds of writing. There are two main reasons for this. First, the algorithms incorporate autocorrecting and autocompleting features, which reduce the number of required corrections and the number of clicks to write a text. Second, their hardware does not need to support underwater usage, so it can weigh less and contain better buttons. Although the autocorrection and autocompletion can be added to our solution, the hardware limitations will remain, so we can still expect a lower speed of writing.

The following points are derived from the results and can be extrapolated in general for selection and input techniques designed for divers interacting with devices under water:

– 2-DOF methods (the QWERTY keyboard) can provide a broader range of angles per key than 1-DOF methods (the Fan keyboard), leading to lower times of aiming and clicking, a lower number of misclicks, and a higher speed of writing.
– On the contrary, 2-DOF methods require a better setup and must be set for a specific situation. Especially, manipulation with these 2-DOF input devices is problematic if the central point in one of the DOF is not set correctly.
– The two-step methods (the Fan2 keyboard) reduce the number of options the user must choose, which allows them to increase the range of angles and ease hitting the keys. This leads to a decreased time required for aiming and clicking and reduces the number of misclicks. However, the necessity of making two steps increases the time required to write texts, so the overall performance depends on the problem and the environment in which the input technique is used. If the number of errors and misclicks is low, the benefit of their reduction that appears in two-step input techniques is too low and may not balance the requirement of making two steps. Regardless, the reduced number of misclicks and times required to aim at the key and click on it also leads to higher user satisfaction, which may counterbalance the increased time required for solving the problem.

6 Conclusion

We have presented a novel method to input texts in underwater environments that enable divers to operate a smart device in a waterproof housing by tilting the device without any access to it. We introduced three different types of underwater keyboards, the 2-DOF QWERTY keyboard, the 1-DOF Fan keyboard, and the two-step 1-DOF Fan2 keyboard.

The user study clearly demonstrated that participants made the least number of mistakes when they used the Fan2 keyboard, and due to the mistakes, writing with this keyboard was faster than with the other two keyboards even though users require to do two clicks to write a single letter.

The Fan2 keyboard was also the most preferred keyboard according to the personal opinion of the users. Our results also showed that 1-DOF keyboards (the Fan and Fan2 keyboards) are more suitable for divers operating in various postures under water since they need not be adjusted for various neutral poses. This was a significant problem of a more common 2-DOF keyboard (the QWERTY keyboard).

The keyboards can be further extended with auto-correct and auto-complete features that would reduce the number of required clicks. Another consideration is using a better distribution of the keys or swipe gestures as presented in [29]; however, this will require the users to spend some time with training to learn the distribution of keys, and the usability must be tested in environments where the users are more prone to make misclicks, like divers under water.

There are several limitations of this study. The first one concerns the robustness of the waterproof housing used. The interaction is relatively limited, and a better interface would ease access to the mobile device. This is a potentially right future direction for the manufacturing sector of waterproof housing devices.

The second limitation is linked to the fact that the study was performed in a controlled environment. Visibility is excellent and typically static compared to open sea environments (although it is not expected to be a significant issue when the conditions are bad since the distance between the device and the diver is small). Moreover, in the open sea environment, there are currents or any other distractions. On the other hand, performing the study in a controlled environment makes collecting the data much more reliable.

Another limitation of this study is that there are differences in conditions between both groups of participants, as it is nearly impossible to provide the same conditions for a similar test. However, although the environment of the test on land was quieter and without additional people, the observations indicate that it had no or negligible effect on the results.

We have successfully piloted the concept of the keyboard in the open sea environment, and performed the user study in by non-experts a controlled environment. Next direction of this research is to experimentally evaluate the Fan2 keyboard in the open sea environment by professional divers and comparing results with those of the controlled environment. We expect that the main strengths and weaknesses of the keyboards, as described at the end of Section 5, will be the same, although the exact numbers will be different.

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Availability of data and material Data of the tests and user feedback are attached to the manuscript as supplementary materials in electronic form.

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