RüttelFlug – A Wrist-Worn Sensing Device for Tactile Vertical Velocity Perception in 3D-Space

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ABSTRACT

Engine-less flight like Paragliding or Hang Gliding heavily relies on leveraging thermals to prolong the experience. At the same time, descending air currents or abnormal weather conditions potentially lead to extreme sink or lift, endangering the pilots. So-called variometers measure the vertical velocity and use auditory and visual encoding to inform pilots of their movement. However, this is often perceived as intrusive, as the loud sound of the devices can spoil flying experience or distract the pilot, especially during takeoff and landing. Vibrotactile cues offer an alternative to communicate velocity changes unobtrusively. This paper presents *RüttelFlug*, a wrist-worn tactile variometer. We conducted initially a formative study to explore suitable vibration patterns that can clearly be distinguished by users. The system was implemented and evaluated in-flight by experienced paraglider pilots, who rated the system as attractive and unobtrusive.

Author Keywords

Haptic Interaction; Tactile Display; Wearable Variometer; Wrist-Worn; Vibrotactile Patterns; Calm Technology

ACM Classification Keywords

H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces - Haptic I/O

INTRODUCTION

While the velocity of up- and downwards movement in 3D-space is not relevant for most activities, for air sports like paragliding and hang gliding such knowledge is crucial for a long, safe and pleasant flight [11]. Because of its engineless nature, the paraglider has to exploit thermals (areas of rising air) to gain altitude and extend the flight. While there is no legal obligation to use one, virtually every pilot has a so-called *variometer* as a tool to measure the vertical velocity of her movement in 3D-Space. Variometers encode velocity as auditory and visual signals, enhancing the pilots' capabilities to extend the flight time or avoid dangerous zones.

Figure 1. *RüttelFlug* is a wrist-worn tactile variometer, e.g. for paragliding. It was designed to be unobtrusive and fits well even under thick clothing.

A problem is, that due to noise of the glider and air stream, variometers have to be comparatively loud to be heard by the pilot. This spoils flying experience and in worst-case can even be dangerously distracting. As stress levels are elevated in paragliding [2] stress sources should be minimized.

In this paper we propose and explore the use of vibrotactile cues to communicate the up or downward velocity in 3D-space. We present the design and implementation of *RüttelFlug*, a wrist-worn information appliance that measures vertical velocity with a pressure sensor and relays the information via tactile output with two vibration actuators. We measured users' ability to discriminate vibration patterns in a lab study with 13 participants and evaluated the whole system in two studies with four and two paraglider pilots. Our results indicate a good differentiability between the developed patterns and an unobtrusive user experience.

BACKGROUND & RELATED WORK

Modern variometers provide the pilot with a multitude of useful information besides vertical velocity, such as air speed, speed over ground and location. In contrast to that, the design concept underlying *RüttelFlug* is that of a minimalistic information service with only the core functionality that is absolutely needed. Other research efforts also focus on connecting variometers with each other to form a distributed real-time detection system for thermal hotspots [12]. This allows pilots in one area to pool their knowledge regarding the present thermals. While *RüttelFlug* is designed as a single user information service, the collected information could easily be disseminated via the optional Bluetooth module (see below).

While there has been extensive research on the stimulation of the skin senses to expand our perception of our environ-

The definitive version was published in ISWC'16, `http://dx.doi.org/10.1145/2971763.2971795`

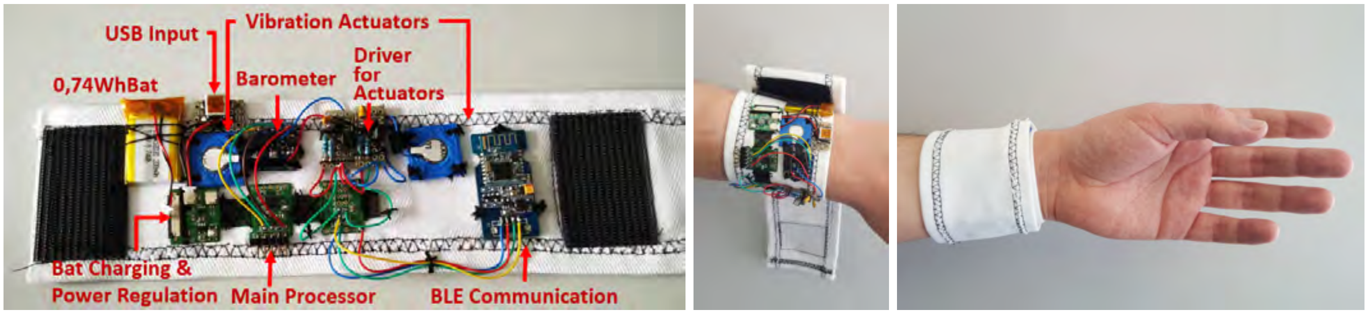

Figure 2. The *RüttelFlug* wristband prototype is built based on a flexible *Seeeduino Film* development platform and features two *Shenzhen Anda Electronic ANDA-B1020* vibration actuators, a *Bosch BMP280* barometric pressure sensor and a *Grove BLE v1* Bluetooth module for communication with smartphone for data logging. Its wriststrap is designed to cover the electronics when closed (right hand side).

ment [7], to our best knowledge none of this was applied in wearables for paraglider or glider pilots. Specifically, Brown and Brewster [4] proposed the concept of so-called *tactons* to transfer information easily via tactile feedback. Tactons are structured abstract tactile icons to communicate with the user in a non-visual way. Brown et al. [5] later showed, that users reached a 93% recognition rate for different rhythms of three successive tactons. This work incorporates patterns of tactons to relay information in a similar way.

Kaczmarek et al. survey technology, definitions and implications of sensory substitution, i.e. using one human sense to receive information normally received by another [10]. While the tactile information flow is generally slower than speech (40 bits/s) or reading (30 bits/s), vibrotactile substitution systems can still be reliably used to transfer information with 5 bits/s. This is more than enough to communicate a set of different states, as done in this work for vertical velocity change.

SYSTEM DESIGN

RüttelFlug was designed as an information service and its design follows the guidelines proposed by Gemperle et al. [9] in being lightweighted, small, worn on the skin and exible. The system satisfies the need of being inside the proxemic aura of the pilot [8]. The form language of the *RüttelFlug* is very simplisic in only being a piece of clothing which entwines the wrist of the pilot (see Fig. 2). Important requirements for the *RüttelFlug* design were:

- *Minimalistic:* In contrast to conventionel variometers, *RüttelFlug* provides only the core functionality of informing the pilot of the vertical velocity of the glider.
- *Non-Intrusive: RüttelFlug* is silent and doesn't distract the pilot with loud noises or otherwise.
- *Low Maintenance:* The pilot does not need to interact with *RüttelFlug* while flying, nor can she as the only possible interaction is turning it on and off.

The design of the *RüttelFlug* system was informed by interviews with four experts (general requirements, system interaction) before start of the system design. Additionally, six single-subject tests concerning the wearability of the system were conducted with both experts and non-experts in an agile process while designing and building iterations of the system. Experts (1 experienced paraglider, 3 paragliding instructors, 1 tailor) reported in open interviews of about 30 minute length. In a workshop session with the tailor various fabric, sewing and attachment options where discussed leading to the design in Fig. 2.

Hardware. As shown in Fig. 2, *RüttelFlug*'s electronic components are sewn onto a cotton wristband of ca. 6.5cm width and an average thickness of 3mm. The prototype is based on a Seeeduino Film microcontroller board (Atmega168) and powered by a rechargeable LiPo-battery pack with a capacity of 200mAh. For measuring of altitude changes, a Bosch BMP280 piezoresistive barometric pressure sensor is integrated via I2C. Two Shenzhen Anda Electronic Co., Ldt. ANDA-B1020 coin type coreless vibration motors (amplified via drivers, 2mm size, packed in custom 3D printed housing) are used for user interaction. A Grove BLE v1 shield with a Bluetooth V4.0 HM-11 BLE Module (TI2540) was connected to the Arduino via UART temporarily in order to enable data logging for evaluation. Vibration actuators were placed 8cm apart from each other to be placed on opposite sides of the wrist when worn (see Fig. 2).

Wearable Sensing. The human skin is the largest and most important sensory organ together with eyes and ears [3]. Vibrations are mostly felt with Pacinian corpuscles which react to excitation frequencies from 40 to >500Hz [1]. Although the perceptive region of the Pacinian corpuscels is quite large we counteracted the weaker spatial resolution of vibrations in maximizing distance between vibration actuators by placement on opposite sides of the wrist and chose vibration patterns as a reliable way to transfer information [9]. *RüttelFlug* samples the barometric pressure every 50ms. The BMP280 is very sensitive but also shows considerable noise which requires 20× oversampling to read stable values (overall sample cycle=1Sec). Raw values are computed to standard atmospheric sea level pressure using the internal calibration settings of the BMP280. Velocity is then calculated as the difference in air pressure of two measurement times measurement interval.

Vibration pattern design. Paraglider experts reported that not absolute velocity values but certain classes of sink/ascend situations are of interest to a paraglider. Consequently the velocity value has to be coded into an information representing a velocity situation class rather than just transfer the velocity into an analogue output (e.g. vibration frequency) value.

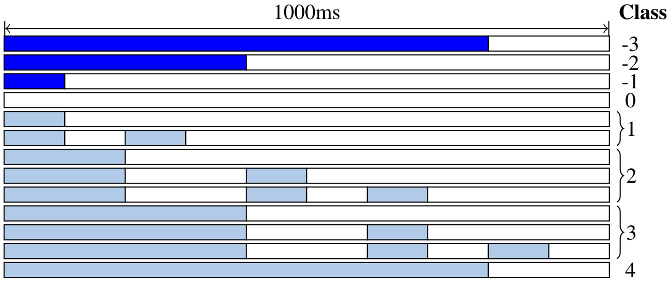

Figure 3. Vibration Patterns: Wrist: Inside (Blue), Wrist: Outside (Light Blue).

Actuator Position	800ms	400ms	200ms	100ms
Wrist: Outside	95% (0.18)	85% (0.22)	90% (0.21)	100% (0.00)
Wrist: Inside	90% (0.16)	87% (0.22)	77% (0.39)	95% (0.13)

Table 2. Success rate (and std.dev.) of vibration length recognition.

Actuator Position	Visual Cue	First Half	Second Half
Wrist: Inside	YES	77% (0.19)	92% (0.12)
Wrist: Outside	YES	87% (0.19)	92% (0.14)
Wrist: Inside	NO	82% (0.20)	91% (0.10)
Wrist: Outside	NO	88% (0.09)	92% (0.09)

Table 3. Success rate (and std.dev.) of vibration pattern recognition.

This concept is in contrast to the working principle of existing variometers where e.g. a sound cue gets louder and faster continuously based on the velocity of a paraglider.

Together with one of the experts 8 classes of vertical velocity (Tab. 1) have been identified. Classes are non-linear ordered to velocity values because they depend on paragliding situation rather than physical measurements. The velocity classes represent also situations that indicate standard behavior for a safe paragliding trip. Because of this, but also because higher resolution is required for certain paragliding maneuvers in some of the classes, subclasses have been assigned to certain classes in a second step.

For coding each class a vibration pattern is assigned. Subclasses result in a variance of the basic vibration pattern of the class. Weak sink was identified as the zero situation, so no pattern is assigned. The number of subclasses can be found in the last column in Tab. 1. The next section will present the initial pattern assignment and some results from experiments when using the *RüttelFlug* device with these patterns.

EVALUATION

Lab Evaluation. We initially proposed the vibration patterns seen in Fig. 3. Patterns for sink (blue) are applied to the vibration actuator *inside the wrist*, patterns for lift (light blue) are applied to the vibration actuator *outside the wrist*.

For initial evaluation of the vibration patterns, we invited 13 participants (12m, 1f) between the age of 19 and 66 (median 23) to our lab. Participants were instructed to solve 3 overarching tasks with up to 3 subtasks in up to 45 minutes.

Tasks are always executed in the same order but the order of the vibration actuator tested (above wrist, below wrist) are randomized. Details of tasks and subtasks are explained briefly beforehand. Then participants were fitted with the *RüttelFlug* wristband to execute the tasks and instructed to sit in an upright position, holding the arm fitted with the *RüttelFlug* in a vertical position.

Velocity [$\frac{m}{s}$]	Category	Implication	Class	# Sub
< -2.5	abnormal sink	leave area!	-3	1
-2.5 to -1.5	strong sink	leaving area advised	-2	1
-1.5 to -0.5	normal sink	glider sink	-1	1
-0.5 to 0.0	weak sink		0	1
0.0 to 0.5	zero lift	active flying	1	2
0.5 to 2.0	weak thermal	circling possible	2	3
2.0 to 4.0	thermal	circling advised	3	3
> 4.0	strong thermal	hang tight	4	1

Table 1. Rate of vertical velocity and its implications.

Vibrations of length 800ms, 400ms, 200ms and 100ms were applied to the one of the vibration actuators. Participants were asked where the vibration was coming from. No training was given. The 800ms vibrations were detected correctly in 97.6% (SD 0.04) of times. The 400ms and 200ms were detected with 100% accuracy. The 100ms vibrations were detected correctly in 90.7% (SD 0.16) of times.

Participants were asked to recognize and name the length of the vibrations. They had a brief training phase, demonstrating each vibration once on both vibration actuators seperatly. The results are shown in Tab. 2.

Participants were asked to identify vibration patterns for lift (see Fig. 3) with and without the help a visual cue listing the patterns. The visual cue consisted of a printout of the patterns for lift (see Fig. 3). In a brief training phase every pattern was applied on both vibration actuators seperatly. Each test iteration applied 20 vibration patterns. We tested the recognition with visual cues first and without cues second. Results are plotted in Tab. 3.

Using a visual cue participants had a recognition rate of 89% (SD 0.16) outside the wrist and 84% (SD 0.14) inside the wrist. Without visual cue the recognition rate was 90% (SD 0.07) outside the wrist and 87% (SD 0.12) inside the wrist. We noticed that nearly all of our participants improved considerably during the experiment. This is shown in Tab. 3 where in all iterations mean recognition rate went up and standard deviation improved from the first 10 patterns and the next 10 patterns of an iteration.

First Field Evaluation. For our first field evaluation we recruited four male paragliding pilots between the age of 22 and 29 as participants. Experience level spanned from intermediate to expert, all were used to flying with conventional variometers. We used the velocity categorization seen in Tab. 1 and vibration patterns described in Fig. 3. During the evaluation we were faced with cold weather thus participants wore layers of (thick) clothing above *RüttelFlug* (see Fig. 1).

The participants were fitted with *RüttelFlug* and briefed for 10 to 15 minutes in using and interpreting it. Particpants were

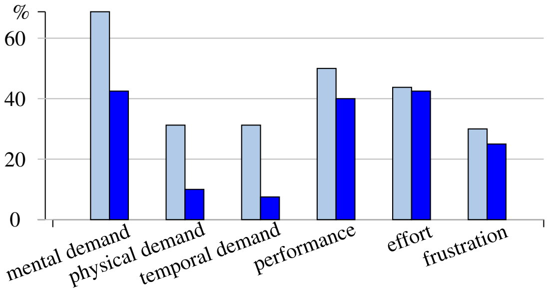

Figure 5. Raw TLX: first (light blue) and second (blue) field evaluation, lower is better.

asked to fly with *RüttelFlug* and their own variometers until they felt comfortable using only *RüttelFlug*, at which point they should independently switch of their variometer and only fly with *RüttelFlug* feedback.

After the flight participants filled out a Raw TLX [6] survey regarding usability of *RüttelFlug* (see Fig. 5) and answered questions regarding their flight experience with *RüttelFlug*. Of the four flights two were very short (10 minutes, no thermal), two flights were of medium length (45 and 60 minutes) with thermals. All participants reported problems localizing vibration sources for 100ms (zero lift or normal sink) and deciding accordingly. All participants were able to differentiate between patterns and use them to circle efficiently in a thermal if present. Overall idea and concept of *RüttelFlug* was well liked due to its silent and non-intrusive nature. All participants were positive that with more training *RüttelFlug* would be a viable alternative for conventional variometers.

Figure 4. Optimized Vibration Patterns for sink (Wrist: Inside).

Second Field Evaluation. We changed vibration patterns for sink after the feedback of our first field study to allow for greater differentiability between sink and lift patterns (see Fig. 4). Our updated System was evaluated by two experienced male paragliders (age 25 and 30) who were used to variometers. The evaluation design stayed the same. Both participants were able to use and interpret *RüttelFlug* to center thermals. Although the the difference between zero lift and weak sink was reported as ”subtle”, none of them had problems telling them apart. One participants wore *RüttelFlug* for over two hours (2 flights) and praised it on it’s non-obtrusiveness where he only felt it when he ”wanted to feel” it. Our preliminary results of the Raw TLX results (see Fig. 5) by our two pilots suggest a lower mental demand, increased performance and reduced frustration. We attribute this to the better differentiabiliy between zero lift and sink.

CONCLUSION AND FUTURE WORK

We designed and evaluated *RüttelFlug*, a wrist-worn variometer that employs a novel approach of communicating vertical velocity to paragliders. We iteratively designed a set of vibration patterns that have a high differentiability and learnability. Participants in a lab study and two real-world field studies were able to distinguish patterns quickly and learned “to feel the vertical velocity”. In the two field studies, experienced paragliders used *RüttelFlug* in-flight and rated the final pattern design as enjoyable and unobtrusive. In the future, we will improve robustness and simplicity of technical design to allow for evaluating the usability of *RüttelFlug* in larger studies with more pilots..

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