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.

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-
...tion [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 lightweight, small, worn on the skin and exible. The system satisfies the need of being inside the proxemic aura being lightweighted, small, worn on the skin and exible. The sign follows the guidelines proposed by Gemperle et al. [9] in RüttelFlug SYSTEM DESIGN different states, as done in this work for vertical velocity change.

In a workshop session with the tailor various fabric, sewing and attachment options where discussed leading to the design 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.

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 corpuscles 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.

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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 overlapping 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.

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 separately. 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. Participants were
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 thermals), 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.

**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.

**REFERENCES**