Introducing a Spatiotemporal Tactile Variometer to Leverage Thermal Updrafts

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Figure 1: Tactile Variometer worn underneath normal flight gear. The pilots movement is not restricted and the cuff fits under normal clothing. Taken during the evaluation in Fellering, France.

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Abstract
Measuring and displaying the vertical velocity of the paraglider is vital to the pilot to extend the flight or to avoid danger. With so-called variometers the vertical velocity is displayed through auditory and visual cues. This paper presents a 6-channel tactile variometer cuff that uses clockwise and counter-clockwise rotating spatiotemporal vibrations to inform the pilot about the current vertical velocity. The system was implemented and evaluated by paraglider pilots in-flight. The pilots were able to extend their flights and use the cuff to stay in thermals using the tactile variometer.

Author Keywords
Haptic Interaction; Tactile Display; Wearable Variometer; Tactile Cuff; Vibrotactile Patterns

ACM Classification Keywords
H.5.2 [Information interfaces and presentation (e.g., HCI)]: User Interfaces - Haptic I/O

Introduction
Engine-less flight like Paragliding or Hang Gliding is heavily reliant on columns of rising air (i.e. thermals). These thermals are leveraged to gain altitude, which then can be transfered in (horizontal) distance and flight time. To detect thermals paragliders often use so called variometers. Variometers permanently measure airpressure and calculate

Figure 2: Cuff: Pockets with actors inside

Figure 3: Worn cuff

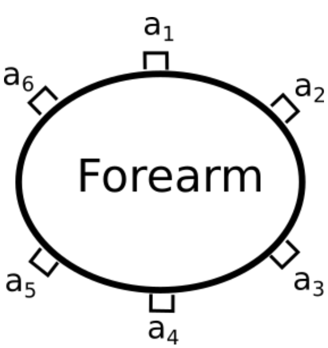

Figure 4: Cross section of the worn cuff

Engine-less flight like Paragliding or Hang Gliding is heavily reliant on columns of rising air (i.e. thermals). These thermals are leveraged to gain altitude, which

the current height and vertical velocity of the paraglider.

The vertical velocity is typically presented visually and/or through accoustic sounds to the paraglider. In this paper the vertical velocity is called climb rate, which also can be assigned with a negative value.

Vibrotactile Feedback

We want to use vibration as a communication channel between the vario and the user (the pilot). This approach is called vibrotactile feedback. There has been related work that investigates the use of vibrotactile feedback in this and other use cases, such as (field-) navigation tasks [1], [3] or experiments in guiding arm movements [4], [2].

Pescara et. al. proposed a wearable tactile variometer which encodes different velocities to tactile patterns [5]. They used vibrotactile tactons (i.e. a vibration rhythm) to inform the pilot about the current climb rate [5]. Since the pilot has to remember the tactons, the number of different tactons was limited. Due to this limitation a mapping was made between a climb (or sink) range (instead of the exact rate) and the tactons.
In this paper we build on the tactile variometer proposed by Pescara et. al. by using circular tactile patterns to inform the paraglider about their vertical velocity, instead of graphically or accoustic feedback.
Since a pilot is interested in smaller variation of the climb rate to use a thermal most effectively, we focused our design on a vibrotactile display that is capable of providing the pilot with exact climb **rates** rather than **ranges**.

System Design

We developed a scuff which is mounted with six vibration actuators (**actuators**). We used the technical system described by Diener et. al. (2017) with vibration actuators from Adafruit (Product ID 1201) and TI TLC5971 drivers to allow chaining actuators together with the SPI-like protocol of the drivers. As described by Diener et. al. (2017) the central unit is the nRF51822 chip on the BLE Nano Board (16MHz, 256 KB Flash, 16KB RAM) [6]. The vibration motors are thin (2.7 mm) and leightweight (0.9 g) and produce vibration patterns at a comfortable and noticeable frequency of 121 Hz at 3.3V [6]. As pressure sensor we used a BME280 piezoresistive pressure sensor. The whole system is powered by a 730 mAh LiPo-battery pack [6].

The microcontroller, battery and a pressure sensor are also included in the cuff (see Figure 2). The cuff is worn on the forearm and can be easily zipped on and off. The actuators are placed in the bottom part of the cuff (which we defined as 'near the ellbow') and form a 'ring' around the arm when worn (see Figure 3). The actuators are ordered from a_1 to a_6. For the actuator a_k the right neighbour is a_{k+1} and the left neighbour is a_{k-1} (see **??**). These six actuators together, are the **vibrotactile display** of the scuff.

Signal pattern

We propose three different signal patterns shown in Figure 5, Figure 6 and Figure 7. The patterns are described as follows.

For the **simple loop** a single actor is activated in each step for a certain *activation time* t. In the next step the actor is deactivated and the neighbouring actor is activated (see Figure 5).

For the **cross loop** pattern there are always two actors active. At the beginning of each step, the current active actors change from a_{k-1} and a_k to a_k and a_{k+1} (see Figure 6).

The **incremental loop** pattern activates at the beginning of each step one additional actor. When all actors are active,

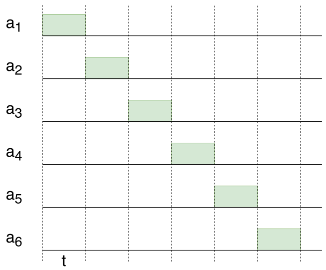

Figure 5: Simple loop

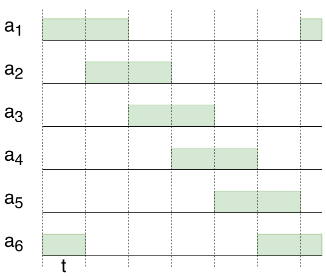

Figure 6: Cross loop

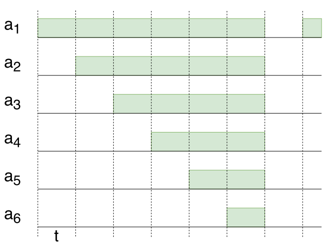

Figure 7: Increment loop

Three different patterns for a signal with fixed t.

the next step deactivates all actors and the procedure starts at the beginning (see Figure 7).

Signal configuration

We used the configuration to encode the current climb/sink rate and present the corresponding signal permanently to the pilot. The configuration is altered immediately if any change of the climb/sink rate occurs and is updated without interrupting the signal.

The **speed** of the signal is used to encode the absolute value of the climb rate. A higher climb rate leads to a faster signal speed and a lower climb rate relates to a slower signal speed. The climb rate c was mapped to the activation time t as follows:

$$t = \max\left(100, 1500 - 300 \cdot |c|\right)$$

Where the unit of c is $\frac{m}{s}$ and the unit of t is ms.

With six actuators the frequency (rounds per second) f is:

$$f = \frac{1000}{6 \cdot t}$$

t is limited since very fast signals aren't well perceived by the users. Limiting t to a value of at least $100ms$ (or $f = 1.67\frac{r}{s}$) is eqiuvalent to an absolute climb rate of $4.66\frac{m}{s}$. Although higher climb rates can occur, this is sufficient to our scenario as the typical climb range is between $-4\frac{m}{s}$ and $4\frac{m}{s}$.

The **direction** of the configuration is used to encode whether the climb rate is positive or negatve. I.e. if the glider is climbing or sinking.
Positive climb rates lead to a clockwise direction, negative climb rates to a counterclockwise moving signal.

Pattern	climb rate (c)	frequency (f)
simple loop	$(-2\frac{m}{s}, 2\frac{m}{s})$	$(0.19\frac{r}{s}, 0\frac{r}{s})$
cross loop	$(-4\frac{m}{s}, -2\frac{m}{s})$, $(2\frac{m}{s}, 4\frac{m}{s})$	$(0.56\frac{r}{s}, 0.19\frac{r}{s})$
incremental loop	$(-\infty, -4\frac{m}{s})$, $(4\frac{m}{s}, \infty)$	$(0.56\frac{r}{s}, 1.67\frac{r}{s})$

Table 1: Assignment of the pattern depending on climb rate (c) and the corresponding frequency (f).

The **pattern** is used to emphasize between weak, medium and strong climb. Different patterns for different activation times are used to enhance the perception of the speed and direction of the signal. We used the three patterns described above. In associating the climb rate with the activation time, a pattern gives also a roughly classification of the climb rate. The assignment between classification and climb rate / frequency / pattern is given in table 1. Although we stated that the signal is not interrupted, there is one exception. To avoid a high frequency direction switching, we interrupt the signal between $\pm 0.07\frac{m}{s}$.

Evaluation

To evaluate the device we asked five pilots to test it during flight. The pilots were equipped with the cuff and wore them directly on the skin beneath all other clothing (see Figure 3). The participants were briefed shortly on the different types of vibration patterns and the different speeds. After the briefing the participants were free to start their flights and fly as long and as often as possible. The participants were asked to file a short questionaire directly after their flight. The questionaires consists of four brief questions: 'Could you recognize if the cuff signalled climb or sink?' (Q_1), 'How well could you, by means of the vibration, center the thermals?' (Q_2), 'Could you recognize if the updrafts

Pilot	A_1	A_2	B_1	B_2	C_1	C_2
Duration (h)	0:10	1:51	0:23	1:48	0:27	0:38
cumClimb (m)	41	2555	362	2121	62	696

Table 2: Duration and cumulated climb of the recorded flights.

Question	Q_1	Q_2	Q_3	Q_4
A_1	4	1	3	3
A_2	5	4	3	5
B_1	4	0	4	4
B_2	3	1	0	5

Table 3: Ratings of received questionaires by participant A and B after their first and second flight. Scale 0 (worst) to 5 (best).

got stronger or weaker?' (Q_3) and 'Did the cuff supported you through your flight?' (Q_4). These questions could be rated from 0 (worst) to 5 (best). A longer interview was conducted after the pilots finished all their flights.

Due to a busy take-off zone only three pilots recorded two flights each (see Table 2). The records contain duration of the flight and the sum of the height gained using updrafts (cumClimb). Also, we received only four filed questionaires (Table 3). The main problem was that the recording of the flights were made with smartphones, which also holds the questionaire. The configuration between cuff and smartphone sometimes took too long, so that the participants proceeded with their flight only wearing the cuff.

A flight typically lasts for seven to twenty minutes, if no updrafts are used at all. Such a flight would also have a cumulated climb of 0. As a rule of thumb one could say, higher cumulated climb leads to longer flights and vice versa. Two of the pilots undertook a flight with a duration of almost two hours. After his first flight, participant A reported that he got along with the cuff very well. However in this flight were only few weak updrafts. On his second flight, the thermals got stronger and he centered some of them supported by the cuff. Participant B was not able to center thermals. However, he reported that he detected weak updrafts with the cuff, which he normally, without any vario, would not have used. On his second flight he gained height through several thermals, without centering them properly.
Although participant C could extend his flights slightly, he mentioned after the first flight that some of the actuators didn't work properly, leading to a non comprehensible perception of the vibrotactile display. After being provided with a working scuff he said it was 'better but not perfect'.

During the interviews some participants also reported difficulties recognizing the direction of the vibration, especially around zero lift situations ($0\frac{m}{s}$). Additionally, the cognitive load to detect the direction of the signal was perceived as high. Some of the participants also mentioned that the speed of the signal was perceived easier than the direction.

Conclusion

In this paper we presented a short overview of our approach of a tactile variometer using a rotating tactile display. We then used this vibrotactile display to support pilots in thermal flights. Our field evaluation with several paragliding pilots has shown that it can be used to support the pilots in extending their flights. While the frequency of the signal was good perceived, our approach to encode a direction in the signal was not effective in our scenario. We suggest long term studies to investigate if there are possible adaption effects to such vibrotactile displays. Also, further studies are required to compare the rotating tactile variometer with other approaches to tactile variometers (see [5]).

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