TactileDrone: Providing Scalable Automated Tactile Feedback for Virtual Reality using Quadcopters

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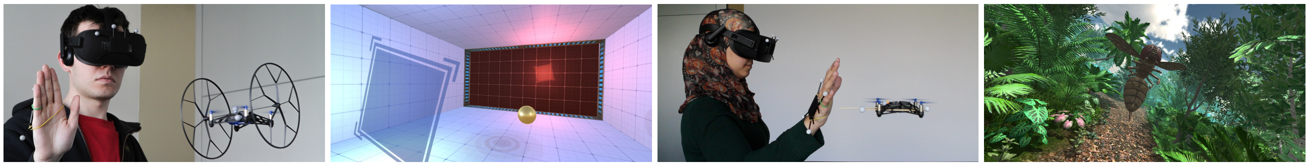

(a) (b) (c) (d)

Figure 1. Two application scenarios for TacitleDrones. a) A user is immersed in a virtual reality Pong game (b) while experiencing haptic feedback by a quadcopter with *wheel* extension. c) User getting poked by a quadcopter equipped with the *stick* extension in a jungle virtual reality experience.

ABSTRACT

Emerging Virtual Reality (VR) systems enables immersive experiences of simulated environments in terms of visual and auditory perception. Regarding tactile feedback, current realizations require users to carry physical controllers. This approach requires user to occupy at least one hand and lacks of body specific feedback. Alternative solutions, such as tactile vests or electrical muscle stimulation, requires additional body-worn devices. We present TactileDrone, a system providing tactile feedback at specific body parts leveraging quadcopters to provide tactile feedback in VR settings. Using an optical tracking system, users and quadcopters are tracked in an accessible 3D space. When a user expects tactile feedback during a VR experience, tactile stimulation through quadcopters is delivered by hitting or touching users at mapped body parts in reality, while remaining both hands free. We describe the design of a TactileDrone prototype and report user experiences for two different VR scenes.

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

Author Keywords

Authors' choice; of terms; separated; by semicolons; include commas, within terms only; required.

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INTRODUCTION

Current VR technologies, such as the Oculus Rift and the HTC Vive, enable the creation of highly immersive environments close to reality. The devices' high-resolution near-eye displays combined with surround sound increases the audio-visual experience and reduces the difference between VR and reality. A key difference between current VR and reality that still exists is the lack of haptic feedback. Apart from feedback provided through handheld controllers, haptic feedback is barely used in VR. This lack of haptic feedback breaks the illusion of experiencing virtual worlds.

A number of research prototypes have been developed, trying to tackle this challenge and provide realistic whole body haptic feedback in VR. These solutions, however, mainly require users to attach devices to their body. Wearable devices such as vibro-tactile gloves [5] or belts [17], for example, only provide feedback at specific body locations. Similarly, using electrical muscle stimulation as feedback [12] requires attaching electrodes to the body and does only provide a limited set of feedback locations and types.

In this work, we propose using quadcopters to provide haptic feedback in VR environments. Quadcopters are levitating objects that can imitate arbitrary objects of the VR scene. They can embody flying objects touching the user or been positioned in a way that the user can touch them matching to virtual objects.

CONTRIBUTION

The contribution of our work is threefold: We present (1) TactileDrone, a system providing whole body haptic feedback in VR using quadcopters. Quadcopters are pushing and nudging users in different VR settings. Apart from providing stimuli, TactileDrone adds haptic input by simulating buttons and sliders. Furthermore, we (2) describe application scenarios highlighting the utility of TactileDrone. In a user study (3) we report our findings investigating subjectively perceived realism between shown scene and recognized tactile stimulation.

RELATED WORK

The TactileDrone project is inspired by two strands of research: enabling haptic feedback in VR and quadcopters, which provide haptic feedback.

Haptic feedback in VR

Most commercial VR devices provide haptic feedback through vibrotactile actuators, integrated into handheld controllers. Previous work developed approaches, which provide more realistic feedback. For example, Benko et al. [4] proposed to augment a handheld controller with a device that can convey the shape of an object in VR and its texture using a matrix of 4×4 actuated pins. To overcome the fact that the users still have to hold a controller, Gu et al. [8] are presenting an exoskeleton which is mounted on the user's hand to provide haptic feedback in VR. As the exoskeleton prevents fingers from moving when a virtual object is in reach, the user has the feeling of a real haptic resistance from the virtual object. To provide haptic feedback at different body locations, Signer and Curtin [15] developed a body-worn construction, which is overlayed by holograms for providing a tangible and haptic Augmented Reality (AR) experience. Systems using this technique will soon become commercially available (e.g. Merge VR[1]).

To provide highly realistic haptic feedback, Simeone et al. [16] proposed to repurpose objects that are already in the environment of the user. The authors arrange a virtual environment according to the physical environment to use existing objects for their – already existing – haptic capabilities. By scaling this down to an object granularity, Hettiarachchi and Wigdor [10] use the physical properties of objects to spontaneously create haptic experiences.

Another trend is to build systems for providing haptic feedback that is scalable, programmable, and can be placed in the environment. For example, Araujo et al. [1] use a robotic arm and a cube with different surfaces for providing different tactile experiences to a user wearing an head-mounted display (HMD). Depending on where the user touches a virtual object, the robotic arm rotates the cube in a way that always the correct surface is being touched. Furthermore, He et al. [9] suggest using small mobile robots as a haptic proxy for VR tabletop applications. Another system for tabletop has been presented by Follmer et al. [6]. The authors purpose a dynamic shape display for displaying forms and shapes according to the digital input. This can be used to dynamically provide haptic feedback for VR scenarios at a fixed position. Conversely, instead of making the environment scalable, other research focuses on making the user believe that the haptics of the environment is matching the virtual scene. Azmandian et al. [3] propose a technique called haptic retargeting for physical feedback in VR. Thereby, the user's hand is being redirected to touch one single object that is in the user's proximity, while the user believes that multiple objects are being touched.

Haptic feedback using Quadcopters

Since the proliferation of small quadcopters, they are mostly used in Human-Computer Interaction for navigation purposes [2, 11] or as a flying camera [13]. This changed when Gomes et al. [7] proposed BitDrones, quadcopters that can be tracked and controlled with a feedback loop system. The quadcopters are combined with LEDs, screens, and a cage to make them graspable. The BitDrones project is one of the first approaches to using quadcopters as a flying input device. Additionally, Yamaguchi et al. [18] proposed using a quadcopter that is carrying a canvas as a haptic target for a sword fight. In their prototype, they are using the drone as a resistor that the user feels to have hit the enemy.

Overall related work recognized the need for haptic feedback to make VR experiences more immersive. This requires a scalable platform managing quadcopters to stimulate their target at the right body positions. Further, related work used quadcopters as an input device and a haptic target. With the TactileDrone project, we extend previous work by using quadcopters to provide active haptic feedback in VR. Not only can the quadcopters being programmed and react to changes in the VR scenario immediately, we also present four different quadcopter extensions to provide three different haptic experiences. This is complemented by suggesting how input can be designed in VR using quadcopters.

CONCEPT

We envision of TactileDrone as a toolbox for enhanced VR experiences. TactileDrone enables new tangible input and haptic output modalities by communicating tactile feedback synchronized with events happening in VR environments. Motivated to explore possible interaction spaces, we present how TactileDrone is used to act as input and output modality.

Feedback Types

Passive Feedback

- Floating Interface Elements (ich drÃijcke gegen button)

User input in VR is provided by wireless controllers, which occupy at least one hand. With quadcopters flying in around users', TactileDrone excels at receiving input while the hands of users' remain free during interaction. TactileDrone replaces traditional controllers by quadcopters hovering around the interaction range of users'. Quadcopters serve as real world input elements, such as buttons, levers, or graspable items.

Active Feedback

- Active Feedback: (biene drÃijckt gegen mich)

Capable of utilizing the 3D space around users', TactileDrone focuses on providing tactile simulation at certain body parts. By mapping events occurring in VR, which require users' to be notified in a haptic way, TactileDrone stimulates the pertinent body spot. TactileDrone achieves this by flying to the affected subject with a quadcopter to touch suitable body parts. Furthermore, quadcopters can vary in stimulation types.

Mixed Feedback

- Mixed Feedback: (ich bekomme Laserschwert zur Eingabe)

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[1] https://mergevr.com

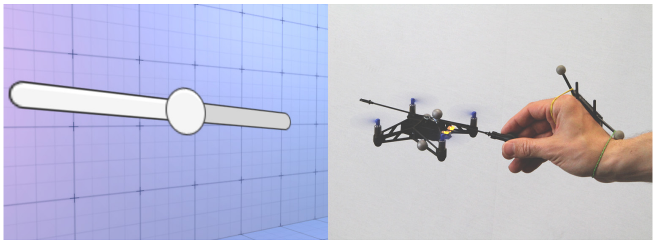

Figure 2. VR adaption of a slider, depicted by a lever attached to a quadcopter in the real-world.

Feedback Properties

Texture, spizitÃď't

Speed, resistance

IMPLEMENTATION

In TactileDrone, each quadcopter represents a haptic feedback or input interface. The system comprises a high-speed motion tracking system, quadcopters as feedback or input interface appliance, a VR HMD and a software component. An overview of all component connections is displayed in Figure 4.

The motion tracking system tracks an HMD, defined body parts, and quadcopters. All data is streamed to the TactileDrone backend. Quadcopters can hover anywhere around the user inside a volume of 4 m × 4 m × 3 m in size. Different light weight extensions, such as markers, can be attached to the quadcopters. Our software backend processes the streamed location data and controls the quadcopter. Furthermore, trajectory planning and synchronization with the virtual world renderer are processed inside this component. We provide TactileDrone source code[2] under an open-source license for replicating the experiments.

Hardware

Our system uses the commercially available Parrot Rolling Spider[3] drone. They are powered by a 550 mAh battery, providing approximately 6 min of flight time depending on the attached extension. We removed all the unnecessary panels to increase the payload capacity. The maximum weight of extension including the markers for the tracking system is 10 g. The quadcopter connects via Bluetooth low energy to our TactileDrone backend. The underlying Linux OS processes steering commands with 20 Hz.

We built four different extensions to reinforce our previously outlined application scenarios. Two to provide proactive haptic feedback and two to support input interfaces. A fifth one can be used for either feedback or input. Extensions are directly mounted to the frame of the quadcopter. All build extensions are displayed in figure 3.

Our VR scenarios are displayed through an Oculus Rift. The VR Headset, quadcopters and the users' hands are set up with reflective markers in a unique configuration, allowing to track their position and orientation in space. We setup a Motive OptiTrack motion capturing system with 12 Flex 3 cameras covering an interaction space of 4 m × 4 m × 3 m. It samples with 100 Hz at a millimeter accuracy.

Software

All software of our TactileDrone prototype runs on a MSI-GT72 laptop with an intel i7 processor and a GeForce GTX 970M running Windows 10. The TactileDrone backend combines three software components. The Motive motion capture software provides location information. A C# application running on this computer processes this data and forwards it to the flight control and the game engine. Further, it maintains quadcopter, users, and interaction states and manages the application behavior.

Flight control

The flight control component wirelessly sends control signals to the quadcopter over Bluetooth low energy to direct it to a particular location. Data transmission is exposed through a local nodeJS application [**?**, https://github.com/voodootikigod/node-rolling-spider] A set of four Proportional, Integral and Differential (PID) loops to control the movement of the quadcopter towards the positions managed by the C# main application. Each PID controller is tuned separately for each extension du to different weight and balance. During hovering, the quadcopter relies on its own IMU, ultrasonic sensor and down facing the camera to stay at a fixed position.

Virtual Reality Renderer

The VR environment displayed at the HMD is rendered by the Unity3D[4] game engine. Like the quadcopters, the HMD is equipped with a set of reflective markers and positional data is forwarded form the TactileDrone core to the rendering engine and the data is rendered accordingly. The game engine is further calculating collisions between virtual objects represented by either quadcopters or human body parts and reports back to the TactileDrone core. As purposed by Schwind et al. [14], we used a neutral hand style representation to avoid potential biases of our participants.

Limitations

Our current implementation of TactileDrone does not support full body tracking yet. Hence, body parts need to be equipped with a reflective marker. This is in particular necessary for interactive application scenarios like Pong or user interface interactions. For scenarios with lower accuracy requirements, the TactileDrone core estimates the body part position depending on the location of the HMD. Using an external motion capturing system in contrast to the specialized tracking hardware of the OculusRift introduced a noticeable latency if moving quickly and could lead to motion sickness. Using the original tracking hardware and fuse the coordinate systems of both tracking system will resolve this issue in future development. Currently, our flight control component supports one flying quadcopter at the time. This limits the frequency of feedback or amount of input interfaces used simultaneously. However, the used Bluetooth stack supports simultaneous connection to up to five quadcopters. Hence, we plan to extend the capabilities of our prototype to support several TactileDrone at

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[3] http://global.parrot.com/usa/products/rolling-spider/

[4] Unity3D: https://unity3d.com

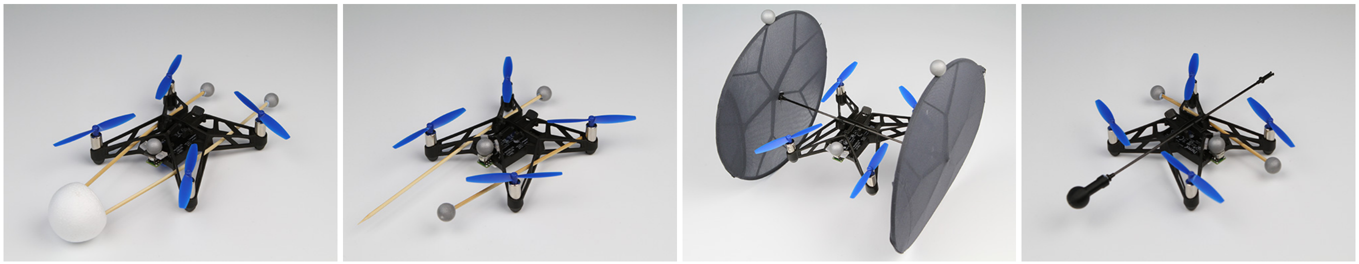
(a) (b) (c) (d)

Figure 3. TactileDrones with different extensions to provide haptic feedback or haptic input interfaces in virtual reality environments. Left to right: a) nudge feedback , b) prick feedback c) a large push button d) a lever that can be pulled

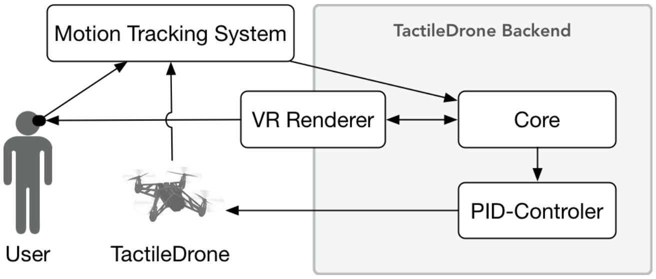

Figure 4. TactileDrone components.

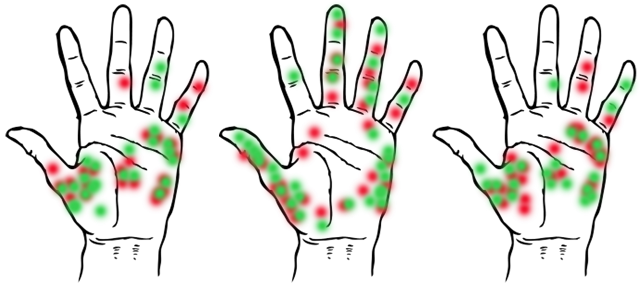
(a) (b) (c)

Figure 5. (a) Examples of the pictures painted by the participants, (b) screenshots of the written text, and (c) photos of the Fitts' dragging task. Green color represents user perceptions, while red color depicts the real position of the quadcopter target.

the same time. Another limitation of our system is that our quadcopters' flight time is limited to 6 minutes and that they produce noticeable audible noise. The latter can be addressed by using active noise canceling headphones.

USER STUDY

To evaluate the feasibility of TactileDrone the quality of haptic feedback in terms of timing, feeling, and strength was investigated during the course of a user study. In this study, quadcopters with three different extensions provide haptic feedback to the participants' hands within two different VR scenes. We measured by means of questionnaires the feeling and synchronicity to the virtual stimuli.

Participants and Procedure

We recruited 6 participants (4 male, 2 female), between 25 and 34 years old (M = 28.1 years) via university's mailing lists. All participants were right-handed and had normal or corrected to normal vision.

After the participants provided informed consent, we introduced the VR headset and TactileDrone including different feedback to the participants. Next, we attached a marker at the back of the right hand to precisely track participants' hands using. Overall, we provided two different virtual scenes to the participant. First, a jungle scene in which the participant is attacked by a bee. Afterwards, the participant was playing a virtual pong game. In each scene, we provided three times haptic feedback with three different types of extensions each. The drone started in the center of the tracking volume, which was approximately 1.5m in front of the user, and accelerated towards the participants' hand in a straight line.

After hand contact, the quadcopter flew back to a safe distance to the hand and started hovering. Afterwards the quadcopter accelerated to contract the hand again.

One of the experimenter asked the questions and the participants answered them orally. The study including introduction and debriefing took approximately 45 minutes.

RESULTS

During the study our TactileDrone system created 106 haptic feedback impulses over all six conditions. We conducted a 3×2 repeated measure ANOVA with the factors *quadcopter extension* and *scenario* on the haptic experience measure. We found a significant effect of scenarios, $F(1,5) = 11.957, p = .018$, however, not on quadcopter extension, $F(2,5) = 1.405, p = .345$, and no interaction of drone $\times$ scenario, $F(2,4) = 2.161, p = .231$. This shows that the user experience significantly depends on the scenario. Figure **??** depicts the perceived haptic feedback position rated by the users (green) and measured by the experimenter (red).

DISCUSSION

We demonstrated how quadcopters can be used to enrich VR systems with haptic feedback.

Accuracy of Feedback

In general, TactileDrone's accuracy is based on the accuracy of the tracking system as well as environmental constraints (e.g., wind, micro-rotations) influencing the quadcopters. As soon as the quadcopters slightly lost its distinct position, the TactileDrone recalculates the position and sends control commands to get the quadcopter back on track. We conducted the user study in a large lab environment and showed that TactileDrone is capable of providing feedback at the user's hand.

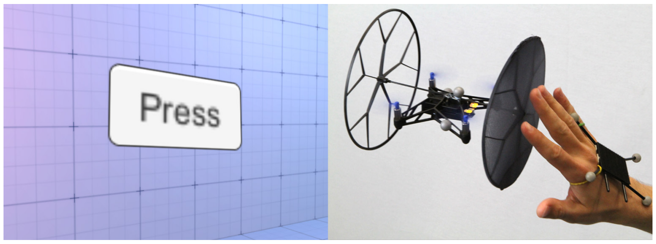

Figure 6. Button press in VR represented by a quadcopter in reality.

Feedback Extensions

We presented four different extensions representing different haptic textures. These four extensions can be used to realize a variety of different feedback methods. In the user study, we compared the three extensions that can be used for haptic feedback simulating the impact of different objects, namely, the nudge, prick and ball. Even though the extensions are rated similarly in some scenes, we believe that overall, this set of feedback extensions helps to design different types of haptic feedback with TactileDrone.

Feedback beyond Virtual Reality

While we developed TactileDrone as a system to enrich VR environments, it became apparent that it is also usable beyond VR applications. Having tangible objects with a closed feedback loop that can be positioned in 3D space can be a powerful interaction tool. Providing important buttons with a tangible mid-air representation can, for example, be used to represent safety critical buttons within the line of sight of the user.

APPLICATION SCENARIOS

We envision to deploy TactileDrone in a number of use cases. Here we demonstrate some implementations to showcase the flexibility of TactileDrone.

Gaming & Entertainment

On coherent story, e.g.: * Active Feedback: Bullets (or something else...) hit the player * Passive Feedback: Player pushes a door to open it * Mixed Feedback: Magic wand is handed to the player

Contruction & Design

* Mixed Feedback: Lenkrad austauschen: Palette an LenkrÃd'dern (100), Nutzer zeigt auf eins, Lenkrad fliegt herbei, Nutzer greift Lenkrad * Passive Feedback: Autos anfassen mit texture (design or shopping) * Active Feedback: Im Windkanal die StÃd'rke des Luftdrucks mit Drohnendruck darstellen

User Interface Elements

One coherent story, e.g.: * Active Feedback: VR is 360, notification of interface elements not currently in the field of view of the user * Passive Feedback: Pushing a button, and sliding a slider * Mixed Feedback: Controller (e.g. a brush) is handed to the user

CONCLUSION

In this paper, we presented TactileDrone, a scalable approach for providing hands-free haptic feedback in VR using quadcopters equipped with three different haptic stimuli. TactileDrone contributes to the field of haptic feedback for VR by providing a framework as an open-source software and thereby enabling researchers and practitioners to use commercially available quadcopters as haptic requisites for creating VR experiences. In a user study, we investigated the subjectively perceived feedback in terms of haptic realism and and perceived hit spots on the hand.

Future Work: Same stuff in AR

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