Tactile Human-Quadrotor Interaction: *MetroDrone*

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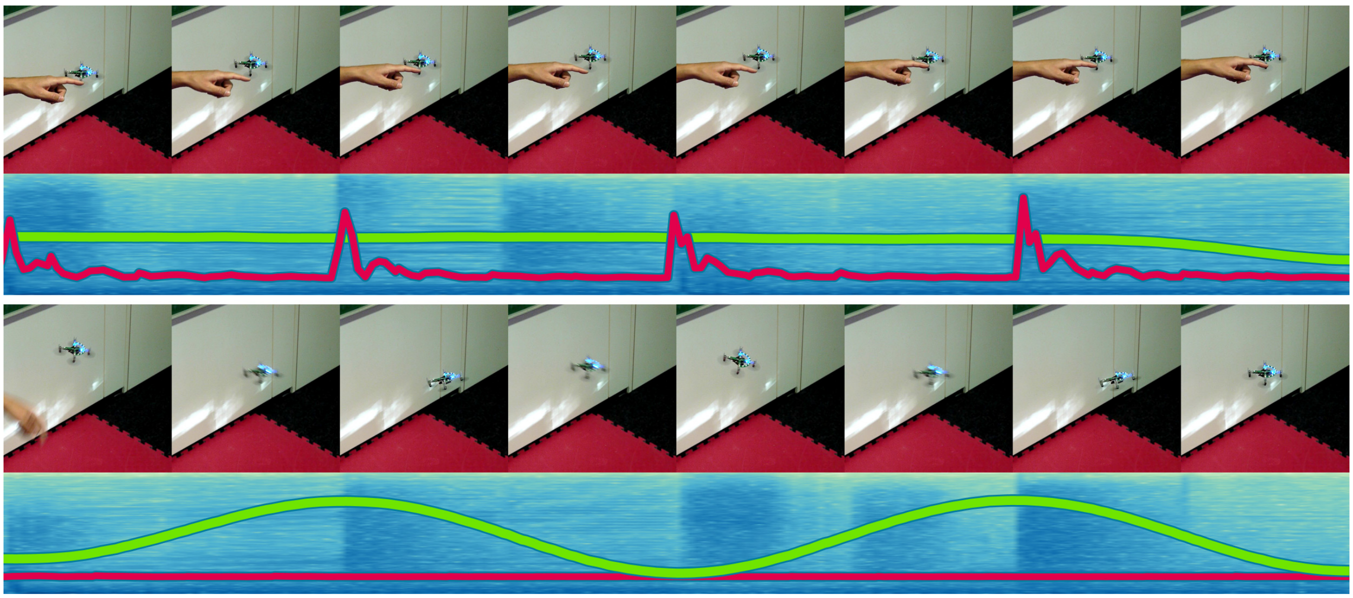

Figure 1: Tactile human-quadrotor interaction sequence with *MetroDrone*: The user taps the frame of the airborne vehicle several times to the beat of the music. Depending on the frequency and direction detected in the change of acceleration measured by the quadrotor's onboard accelerometer, a trajectory is generated that makes the quadrotor move to the beat.

ABSTRACT

Aerial robots such as quadrotors enjoy ever-increasing popularity and emerge in everyday applications that require user interaction. At immediate proximity, physical control of the quadrotor by touch may be desired or even necessary. In this paper we present a tactile 3D touch interaction scenario with a quadrotor by introducing virtual buttons whose operation is detected in the accelerometer data of the built-in Inertial Measurement Unit (IMU) of the quadrotor. By dispensing with additional sensors, we are able to keep the size of the used quadrotor to a minimum and thus address the problem of users being discouraged from interaction with quadrotors at immediate proximity. As an example for the proposed interaction scenario, we introduce *MetroDrone*, a quadrotor responding to repeated user taps to virtually defined buttons by flying trajectories according to the beat and operated button. This introduces a minimalist interaction technique that requires no intermediary devices and strengthens human-robot connections through shared musical experience.

CCS CONCEPTS

• **Human-centered computing** → *User interface design*; **Interaction techniques**; • **Computer systems organization** → External interfaces for robotics.

KEYWORDS

human-quadrotor interaction, non-verbal communication, tactile interaction, quadrotor companions, social robots

ACM Reference Format:

Marc Lieser, Ulrich Schwanecke, and Jörg Berdux. 2021. Tactile Human-Quadrotor Interaction: *MetroDrone*. In *Fifthteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21), February 14–17, 2021, Salzburg, Austria.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3430524.3440649

TEI '21, Febuary 14–17, 2021, Salzburg, Austria

ACM ISBN 978-1-4503-8213-7/21/02…$15.00
https://doi.org/10.1145/3430524.3440649

1 INTRODUCTION

Quadrotors, Unmanned Aerial Vehicles (UAVs) with four rotors, are becoming increasingly popular due to their low cost and mechanical simplicity. Some of them are now fully autonomous, providing first aid for victims in Search and Rescue (SAR) scenarios, delivering medical equipment and parcels or document the endeavors of athletes with aerial videos. It is likely that in future scenarios we will share our homes with more robots, ground-based or of aerial nature, each for different purposes. Just as smartphones already do today on Earth and as robot assistants Astrobee [Bualat et al. 2018] and CIMON [DLR 2019] do on the International Space Station (ISS), small UAVs could support us in the future in our private homes. These scenarios require new interaction techniques that feel more natural than the use of classic radio remote controls or smartphones.

For natural communication at greater distances, several gesture control approaches were proposed [Cauchard et al. 2015; Naseer et al. 2013]. When it's not possible for cameras to capture humans in their entirety and thus pose estimation fails, interaction scenarios from an even closer proximity may be desired. For these close-range scenarios, investigations were made for control by facial expression [Nagi et al. 2014] and voice [Krishna et al. 2015; Ng and Sharlin 2011] as well as multimodal interaction including hand gestures [Cacace et al. 2016; Suárez Fernández et al. 2016]. Most of these contact-free scenarios require additional higher level sensors like depth cameras or motion sensors, either mounted to the quadrotor's frame, permanently installed in controlled environments or attached to the user's body [Calella et al. 2016; Gromov et al. 2019]. At close proximity, direct touch interaction may be required to directly interact with flying interfaces or hovering programmable matter [Gomes et al. 2016]. Also physical buttons have been attached to the frame of a quadrotor in order to enable interaction at immediate proximity [Rajappa et al. 2017].

Haptic communication is a branch of nonverbal communication which refers to the ways people and animals communicate and interact through the sense of touch. Since touch is the earliest sense to develop in the fetus [Coren et al. 1999] it may be the most intuitive way of interaction. Motivated by an interaction method that does not rely on additional hardware, we utilize a novel approach to control quadrotors: 3D touch interaction realized by virtual buttons. Quadrotors are equipped with an Inertial Measurement Unit (IMU), an electronic device that combines several instruments – usually accelerometers, gyroscopes and magnetometers – to measure the force, angular velocity and orientation of the UAV. The IMU is an essential part of the UAV, as it could not fly without it. In this work we utilize the accelerometer data of the built-in IMU for physical human-quadrotor interaction without intermediary devices. By dispensing with additional sensors, we are able to use miniature quadrotors that would otherwise not be able to fly due to the additional weight. With the ability to realize 3D touch interaction, for example, the behavior of hitting the trunk of a vehicle twice after unloading to signal the driver that he can drive off could be transferred to last-centimeter UAV delivery: The vehicle has been unloaded and is ready for departure. Communicating acknowledgement of a satisfactory done job by patting someones shoulder could also be transferred to flying robots, especially since it has been observed that people tend to interact with UAVs as with a person or a pet [Cauchard et al. 2015].

Another problem that we address by using data from existing sensors to keep the size of the robot to a minimum is the higher level of mental stress that people experience when interacting with mechanical-looking robots in such a close proximity [Walters et al. 2005], especially when they are of aerial nature [Acharya et al. 2017]. This results in an inhibition threshold caused by rotor blades and the overall mechanical appearance [Acharya et al. 2017; Yeh et al. 2017]. To counteract safety concerns about exposed rotor blades, they can be fitted with rotor guards resulting in a less mentally demanding interaction [Abtahi et al. 2017]. Furthermore, people tend to encounter quadrotors skeptically due to privacy or security reasons [Chang et al. 2017; Kim et al. 2016]. However, recent research shows positive evidence for having social or service aerial robots in human environments [Yeh et al. 2017], and several use cases of social drone companions for home [Karjalainen et al. 2017] and outdoor applications [Deng et al. 2018] have been proposed.

Apart from anthropomorphism, which is not always an option to make the robot's actions interpretable for humans and thus lowering the inhibition threshold, research focuses on utilizing the trajectories of the quadrotor in order to convey intent or the internal state of the quadrotor. Affect and emotions are communicated through their trajectories [Cauchard et al. 2016; Sharma et al. 2013] and Disney's principles of animation are applied in order to avoid surprises by anticipating the quadrotor's motion [Lieser et al. 2020].

Socially expressive ground robots are well accepted because their movements can be well interpreted by humans. Music listening companions like the Sony Rolly [Kim et al. 2009] or the Keepon [Kozima et al. 2009] are used for research, therapy and entertainment. Research has shown that robots responding to musical experience causes humans to attribute human-like traits to the robot and to rate the robot as more similar to themselves [Hoffman and Vanunu 2013]. The shared experience of emotions evoked by music also strengthens the bond between humans [Koelsch 2013]. In this work we present a scenario to replicate exactly this emotional bond between a human and a quadrotor. Fig. 1 shows a short sequence of the proposed interaction scenario, where the user taps four times to the quadrotor's frame and its response by flying a short trajectory matching the beat.

Instead of using a software to detect the song or the beat, this work aims at the interactive experience where human and quadrotor enjoy music together. This utilizes the proposed tactile immediate proximity interaction without intermediary devices in order to teach the quadrotor a song's beats per minute (bpm), a common measurement of tempo in music. In response, the quadrotor performs a short dance and thus appears to be emotionally responding to music, making it a little less mechanic and intimidating in order to help lowering the inhibition threshold.

In Section 2, the method used to detect tap interaction in the acceleration data of the quadrotor's IMU is presented. Section 3 gives a general outline on how trajectories are generated. In Section 4, the design and implementation of the proposed human-quadrotor interaction scenario *MetroDrone*, where user taps initiate dance moves, is explained. Finally, our work is summarized in Section 5 and an outlook on future research is given.

2 TAP DETECTION

Jerk, the third time derivative of the position vector or the change of an object's acceleration with respect to time, is minimized in most trajectory generators to achieve smooth motion of a vehicle. Thus, without external forces acting on the vehicle, jerk is uncommon under usual flight conditions and is what the method described in the following detects in the quadrotor's accelerometer data.

In order to reject noise, a low-pass filter is applied to the accelerometer data, i.e.

$$\ddot{\mathbf{x}}'_k = \alpha\ddot{\mathbf{x}}_k + (1-\alpha)\ddot{\mathbf{x}}'_{k-1}, \quad \alpha = \frac{\mathrm{d}t}{\tau + \mathrm{d}t},$$

where $\ddot{\mathbf{x}}_k$ is the raw acceleration vector at discrete time k and τ is an empirically determined time constant for two consecutive measurements being separated in time by dt. The jerk vector $\dddot{\mathbf{x}}_k$ at time step k is derived from the filtered acceleration vector by

$$\dddot{\mathbf{x}}_k = \frac{\ddot{\mathbf{x}}'_k - \ddot{\mathbf{x}}'_{k-1}}{\mathrm{d}t}.$$

Now, a potential tap is detected, when the length of the jerk vector exceeds a given threshold, i.e. if

$$\|\dddot{\mathbf{x}}_k\| > t_1.$$

Since a jerk is followed by a jerk along the opposite direction that can also lead to a peak in noisy data, a time period t_2 for which the detection is suspended, prevents the algorithm from double detection.

If just the jerk and its direction are detected, the quadrotor is able to react, e.g., by moving away from the tap source. To identify multiple tap directions in order to respond differently, we introduce a virtual button metaphor by a set of $M+1$ unit vectors given in the quadrotor's body frame

$$\mathcal{R} = \{\mathbf{r}_i, \in \mathbb{R}^3 : \|\mathbf{r}_i\| = 1, i = 0, \ldots, M\}.$$

An example of virtual buttons along with acceleration data caused by interacting with them is shown in Fig. 2.

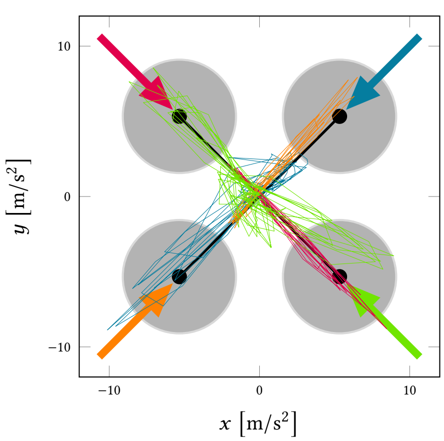

Figure 2: Schematic view of a quadrotor with four virtual buttons illustrated by the direction of their operation and the raw accelerometer data of multiple operations shown in corresponding colors visualizing the virtual button metaphor that defines a button by its normal vector.

The operated virtual button is detected by maximizing the cosine similarity between the normalized, detected jerk direction vector $\hat{\dddot{\mathbf{x}}}_k = \dddot{\mathbf{x}}_k \cdot \|\dddot{\mathbf{x}}_k\|^{-1}$ and the set of virtual buttons, i.e.

$$\mathbf{r}_k = \operatorname*{arg\,max}_{\mathbf{r}\in\mathcal{R}} \mathbf{r} \cdot \hat{\dddot{\mathbf{x}}}_k.$$

If in addition $\mathbf{r}_k \cdot \hat{\dddot{\mathbf{x}}}_k$ exceeds a given similarity threshold t_3, a tap with intensity of $\|\dddot{\mathbf{x}}_k\|$ is detected along $\mathbf{r}_k$. In the evaluation for virtual button presses the intensity does not matter, but if it is desired to react to the intensity of the button operation, e.g., by wider movements, the magnitude of the jerk can be taken into account.

3 TRAJECTORY GENERATION

We describe trajectories as piecewise polynomial functions (see for example [Corke 2013]). Quintic (fifth-order) polynomials are a common choice for trajectories, since their first and second time derivatives — velocity and acceleration — are continuous and thus result in smooth trajectories. Boundary conditions, such as position, velocity, acceleration and time, can easily be set. A scalar trajectory quintic polynomial and its first and second order time derivates, given as

$$\begin{aligned} s(t) &= at^5 + bt^4 + ct^3 + dt^2 + et + f \\ \dot{s}(t) &= 5\,at^4 + 4\,bt^3 + 3\,ct^2 + 2\,dt + e \\ \ddot{s}(t) &= 20\,at^3 + 12\,bt^2 + 6\,ct + d \end{aligned} \tag{1}$$

result in a linear system

$$A_T\mathbf{c} = \mathbf{s}_{[0,T]} \tag{2}$$

with system matrix

$$A_T = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ T^5 & T^4 & T^3 & T^2 & T^1 & 1 \\ 5\,T^4 & 4\,T^3 & 3\,T^2 & 2\,T^1 & 1 & 0 \\ 20\,T^3 & 12\,T^2 & 6\,T^1 & 2 & 0 & 0 \end{bmatrix},$$

polynomial coefficient vector $\mathbf{c} = (a, b, c, d, e, f)^\top$ and condition vector $\mathbf{s}_{[0,T]} = (\mathbf{s}(0), \mathbf{s}(T))^\top$, which combines two boundary states $\mathbf{s}(t) = (s(t), \dot{s}(t), \ddot{s}(t))$ with start time $t = 0$ and end time $t = T$, the duration of the trajectory segment. For $T \neq 0$ the linear system (2) can be uniquely solved for the polynomial coefficient vector $\mathbf{c}$.

The different boundary states $\mathbf{s}_i(t_i)$ for prescribed times t_i can be considered as keyframes. A trajectory $\mathcal{K}$ is then represented by a list of $N+1$ of these keyframes, i.e. $\mathcal{K} = (\mathbf{s}_0(t_0), \ldots, \mathbf{s}_N(t_N))$ and thus consists of N trajectory segments $\mathbf{s}_{[i,i+1]} = (\mathbf{s}_i(t_i), \mathbf{s}_{i+1}(t_{i+1}))^\top, i \in \{0, \ldots, N-1\}$. The corresponding polynomial coefficients $\mathbf{c}_i, i \in \{0, \ldots, N-1\}$ for the respective trajectory segments are determined by solving (2) with $T = (t_{i+1} - t_i)$, i.e.

$$\mathbf{c}_i = A_T^{-1}\mathbf{s}_{[i,i+1]}, \tag{3}$$

which results in the polynomials $\mathbf{s}_i(t), i \in \{0, \ldots, N-1\}$ for the N trajectory segments. These trajectory segments are then sampled at rate f_s by

$$\mathbf{s}_i(t_j), \quad t_j = \frac{j}{f_s}T, \quad j \in \{0, \ldots, f_s\}.$$

For the multi-dimensional vector case, the piecewise polynomials are interpolated independently in each dimension and joined to obtain the final trajectory, that is passed to the controller.

4 METRODRONE

To demonstrate tactile drone interaction, we implemented *Metro-Drone*, a quadrotor responding to interaction by flying different trajectories according to the identified button operated by the user and the detected beat. In the following we provide a short overview of our testbed and the hardware used. We also provide the details of generating a specific flight trajectory and further discuss tactile interaction with quadrotors.

4.1 Testbed

Our low-cost quadrotor testbed *ICARUS* [Lieser et al. 2020, 2017] was continuously expanded and improved over the past years and allows for safe test flights of arbitrary quadrotor models in a simulated environment but also controls real quadrotors. It employs a predictor-corrector estimator similar to the one described in [Lupashin et al. 2014]. Noise from pose estimation is filtered and the quadrotors' states are latency-compensated by the implemented model of quadrotor dynamics summarized in [Lupashin et al. 2014; Michael et al. 2010]. The control loop runs at a frequency of 100 Hz. The hover controller used was presented in [Mellinger and Kumar 2011]. For trajectory control a Model-Predictive Controller (MPC) with a discretization time step $\mathrm{d}t = 0.1\,\mathrm{s}$ and time horizon $t_h = 2\,\mathrm{s}$ is used. The implementation is based on open-source code [Falanga et al. 2018] and uses `ACADO` to set up the optimization problem and `qpOASES` to solve it. While the model parameters remain unchanged, the controller was tuned by experiment and varies from the original implementation: Costs for the horizontal and vertical position errors were left at 200 and 500 respectively, the costs for the attitude error were reduced from 50 to 25 and the costs for the velocity error from 10 to 4. The costs for the thrust, roll and pitch inputs were left at 1 and the costs for the yaw input was lowered from 1 to 0.1. The monocular pose estimation system [Tjaden 2019] multicasts UDP messages that consist of a six degrees of freedom pose and a timestamp. The estimator receives position and attitude from pose estimation and determines velocity and angular velocities by numerical differentiation. Telemetry data is also forwarded to the estimator and includes the current battery voltage to compensate the thrust command for varying voltages. The software for the entire infrastructure, including pose estimation, runs on a single, standard laptop.

For the human-quadrotor interaction scenario described in this paper, a Bitcraze Crazyflie 2.0 is used. The Crazyflie is a great, expandable development platform, which was modified for this scenario by turning it upside down in order to attach an infrared LED-based marker [Tjaden 2019] used for pose estimation. This also allows to use the motor mounts as virtual buttons for user interaction. The hardware modifications made can be seen in Fig. 3. The Crazyflie runs the default firmware in rate mode with onboard battery compensation disabled, since this is done by our testbed implementation. To control the Crazyflie by software and receive telemetry data, we use the `crazyflie_cpp` library [Hönig and Ayanian 2017] and set the rate of acceleration telemetry data to 100 Hz.

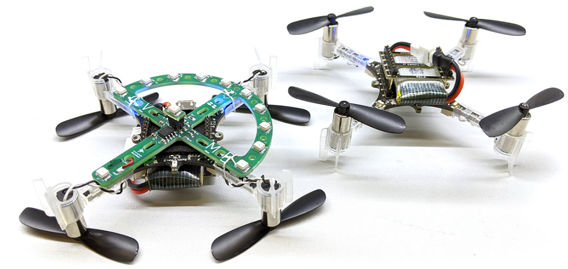

Figure 3: Bitcraze Crazyflie 2.0 with the rotors mounted upside down so they do not obscure the LEDs of the attached tracking marker and an unmodified platform for comparison in the background. With this modification, the motor mounts expose to the top and are used as interaction points.

4.2 Tactile Interaction

In the provided example, interaction is restricted to taps that lie within the horizontal plane of the quadrotor. External, vertical forces applied to points that do not lie in the center of mass of the quadrotor result in tilting the thrust vector and thus attitude destabilization. As an example, applying a downward force to an arm of the frame would result in the quadrotor moving towards the user's finger, which is of course not desirable. For *MetroDrone*, we propose and implement four virtual buttons in the horizontal plane of the quadrotor as shown in Fig. 2, along with the according, unfiltered accelerometer data, this interaction technique is based on. These four buttons are applicable to most quadrotors, but buttons can be defined virtually anywhere, provided a suitable frame or housing is available.

For jerk detection, the low-pass filter time constant $\tau = 0.0025$ and the jerk peak threshold of $t_1 = 400\,\mathrm{m/s^3}$ were chosen by experiment. A detection suspension threshold of $t_2 = 0.2\,\mathrm{s}$ allows the algorithm to detect beats of up to 300 bpm. The cosine similarity threshold was set to $t_3 = \cos(\pi/8)$.

The implemented beat detector collects the timestamps of detected taps (jerk value above peak threshold t_1) along the four specified normal directions that point toward the quadrotor's center of mass. The differences between consecutive timestamps are converted into beats per minute. If the standard deviation of the bpm values within a discrete time window is below a given threshold, the beat detector initiates one of the four dance trajectories shown in Fig. 4. For the examples, we chose a standard deviation of 3 bpm and a window size of four to match 4/4 time signatures, where the first number corresponds to the number of beats in a measure in musical notation. Four user taps thus correspond to the four beats in a measure, and the dance trajectory is then initiated in time for the beginning of the following measure.

A basic, scalar periodic dance trajectory $\mathcal{K}_0$ that implements a side-to-side motion at $f = 2\,\mathrm{Hz}$ (120 bpm) can be seen in Fig. 5 and is constructed from the keyframes

$$\mathbf{s}_i(t_i) = \begin{pmatrix} (-1)^i \cdot d \\ 0 \\ 0 \end{pmatrix}, \quad t_i = \frac{i}{f}, \quad i \in \{0, \ldots, N\}.$$

with displacement $d = 0.1\,\mathrm{m}$.

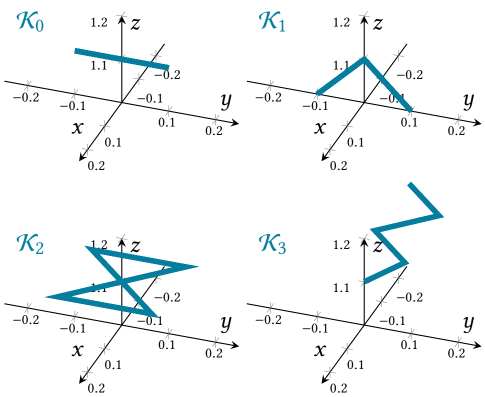

Figure 4: Plots showing the four different dance trajectories of this experiment (all dimensions are in meters).

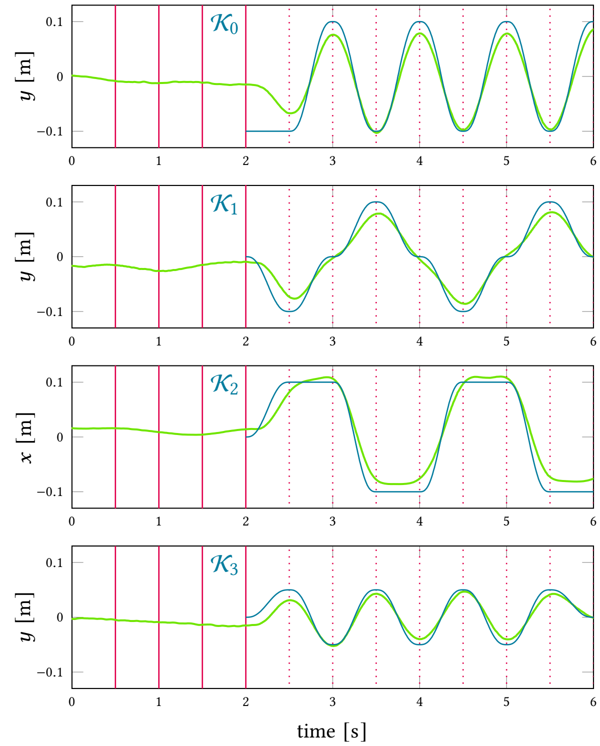

Figure 5: *MetroDrone* interaction sequences: Four taps to a beat at 120 bpm in 4/4 time signature (red), the propagated beat (dotted) to which a trajectory (blue) is initiated and a selected coordinate of the quadrotor's position (green) during flight of the trajectory.

Since the quadrotor should come to rest at the keyframes to emphasize the beat, velocity and acceleration are set to zero. The trajectory consists of $N = 8$ segments in order to be a multiple of the 4/4 time signature and is sampled at a rate of $f_s = 100$ Hz to match the update rate of the flight controller. The other trajectories shown in Fig. 4 and their projections (Fig. 5) are constructed similarly by using different keyframes.

As the fourth tap is detected, the trajectory is generated and executed just in time for the next beat. The time trajectory calculation takes, is subtracted so synchronize the start of the trajectory. The according interaction sequence can be seen in Fig. 1. For more in-depth work on synchronizing quadrotors to music see [Schöllig et al. 2010].

5 CONCLUSION & FUTURE WORK

In this work, we presented a novel technique for human-quadrotor interaction based on the basic human instinct, touch. We demonstrated how we refrain from the use of additional intermediary devices by resorting to the accelerometer data of a quadrotor's built-in IMU and provided a method to detect user tap interaction based on peaks in the signal. In addition, we have introduced virtual buttons and explained how to distinguish them. As an example of implementation, we presented *MetroDrone*, a quadrotor responding to recurring user taps to its frame by initiating different dance trajectories. This way we provided a possible method to lower the inhibition threshold in human-quadrotor interaction by playfully creating a bond between human and robot through shared musical experience. In this interaction scenario physical communication is desired. But at immediate proximity, where sensors that are commonly used for user interaction fail, touch interaction may even be necessary, e.g., as a safety fallback measure to stop a quadrotor from further approaching. Although people tend to feel safer when a quadrotor is equipped with rotor guards, we have deliberately refrained from such features in order to emphasize our minimalist approach. Furthermore, any additional weight considerably reduces the flight time of a miniature-sized quadrotor. Because of the minimalist approach, which repurposed the IMU instead of adding physical buttons or capacitive sensors, the presented method can be implemented on almost any quadrotor system.

The presented interaction possibilities provide the proof of concept for basic physical interaction with quadrotors. Future work includes further elaboration of the proposed interaction by, e.g., incorporating tap intensities. This way the quadrotor could respond accordingly with wider or more reserved movements. Furthermore, adding a spherical housing would provide a sense of safety for the user and at the same time overcome the limitation of virtual buttons restricted to the horizontal plane allowing for arbitrary tap directions. The beat detection method could be extended to work with different time signatures and to learn rhythms and thus would enable a more comprehensive experience. It would also be conceivable to identify the playing song via appropriate services and to query databases for the genre in order to generate genre-specific dance trajectories. In addition to the implemented directional tap interaction, which is limited to taps towards the center of mass of the quadrotor, *MetroDrone* could be further improved by implementing the detection of rotational forces applied by the user based on data of the onboard IMU. With the help of this electronic device, we have taught the robot a sense of touch. Another topic we are currently working on, is to provide it with the sense of hearing by studying the acceleration data for motion caused by sound waves resulting from direct exposure of the quadrotor to a music source.

REFERENCES

Parastoo Abtahi, David Y. Zhao, Jane L. E., and James A. Landay. 2017. Drone Near Me: Exploring Touch-Based Human-Drone Interaction. *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies* 1, 3, Article 34 (Sep 2017), 8 pages. https://doi.org/10.1145/3130899

Urja Acharya, Alisha Bevins, and Brittany A. Duncan. 2017. Investigation of human-robot comfort with a small Unmanned Aerial Vehicle compared to a ground robot. In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. 2758–2765. https://doi.org/10.1109/IROS.2017.8206104

Maria Bualat, Trey Smith, Ernest Smith, Terrence Fong, and Dw Wheeler. 2018. Astrobee: A New Tool for ISS Operations. https://doi.org/10.2514/6.2018-2517

Jonathan Cacace, Alberto Finzi, Vincenzo Lippiello, Michele Furci, Nicola Mimmo, and Lorenzo Marconi. 2016. A control architecture for multiple drones operated via multimodal interaction in search & rescue mission. In *2016 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*. 233–239. https://doi.org/10.1109/SSRR.2016.7784304

Jules C. Calella, Francisco R. Ortega, Naphtali Rishe, Jonathan F. Bernal, and Armando Barreto. 2016. HandMagic: Towards user interaction with inertial measuring units. In *2016 IEEE SENSORS*. 1–3. https://doi.org/10.1109/ICSENS.2016.7808524

Jessica R. Cauchard, Jane L. E, Kevin Y. Zhai, and James A. Landay. 2015. Drone & Me: An Exploration into Natural Human-drone Interaction. In *Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing* (Osaka, Japan) *(UbiComp '15)*. ACM, New York, NY, USA, 361–365. https://doi.org/10.1145/2750858.2805823

Jessica R. Cauchard, Kevin Y. Zhai, Marco Spadafora, and James A. Landay. 2016. Emotion encoding in Human-Drone Interaction. In *2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 263–270. https://doi.org/10.1109/HRI.2016.7451761

Victoria Chang, Pramod Chundury, and Marshini Chetty. 2017. Spiders in the Sky: User Perceptions of Drones, Privacy, and Security. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. ACM, New York, NY, USA, 6765–6776. https://doi.org/10.1145/3025453.3025632

Stanley Coren, Lawrence M. Ward, and James T. Enns. 1999. *Sensation and Perception.* Harcourt Brace College Publishers. https://doi.org/10.1002/9781118133880.hop201007

Peter Corke. 2013. *Robotics, Vision and Control: Fundamental Algorithms in MATLAB* (1st ed.). Springer Publishing Company, Incorporated.

Honghao Deng, Jiabao Li, Allen Sayegh, Sebastian Birolini, and Stefano Andreani. 2018. Twinkle: A Flying Lighting Companion for Urban Safety. In *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction* (Stockholm, Sweden) *(TEI '18)*. 567–573. https://doi.org/10.1145/3173225.3173309

DLR. 2019. CIMON-2 is on its way to the ISS. https://www.dlr.de/content/en/articles/news/2019/04/20191205_cimon2-on-its-way-to-the-iss.html. Retrieved: 2020-12-12.

Davide Falanga, Philipp Foehn, Peng Lu, and Davide Scaramuzza. 2018. PAMPC: Perception-Aware Model Predictive Control for Quadrotors. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '18)*. 1–8. https://doi.org/10.1109/IROS.2018.8593739

Antonio Gomes, Calvin Rubens, Sean Braley, and Roel Vertegaal. 2016. BitDrones: Towards Using 3D Nanocopter Displays As Interactive Self-Levitating Programmable Matter. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16)*. ACM, 770–780. https://doi.org/10.1145/2858036.2858519

Boris Gromov, Jérôme Guzzi, Luca Gambardella, and Alessandro Giusti. 2019. Demo: Pointing Gestures for Proximity Interaction. In *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 665–665. https://doi.org/10.1109/HRI.2019.8673329

Guy Hoffman and Keinan Vanunu. 2013. Effects of robotic companionship on music enjoyment and agent perception. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 317–324. https://doi.org/10.1109/HRI.2013.6483605

Wolfgang Hönig and Nora Ayanian. 2017. *Flying Multiple UAVs Using ROS.* Springer International Publishing, 83–118. https://doi.org/10.1007/978-3-319-54927-9_3

Kari Daniel Karjalainen, Anna Elisabeth Sofia Romell, Photchara Ratsamee, Asim Evren Yantac, Morten Fjeld, and Mohammad Obaid. 2017. Social Drone Companion for the Home Environment: A User-Centric Exploration. In *Proceedings of the 5th International Conference on Human Agent Interaction (HAI '17)*. 89–96. https://doi.org/10.1145/3125739.3125774

Hyun Young Kim, Bomyeong Kim, and Jinwoo Kim. 2016. The Naughty Drone: A Qualitative Research on Drone as Companion Device. In *Proceedings of the 10th International Conference on Ubiquitous Information Management and Communication (IMCOM '16)*. 1–6. https://doi.org/10.1145/2857546.2857639

Jaewook Kim, Sonya S. Kwak, and Myungsuk Kim. 2009. Entertainment robot personality design based on basic factors of motions: A case study with ROLLY. In *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication (2009 RO-MAN)*. 803–808. https://doi.org/10.1109/ROMAN.2009.5326222

Stefan Koelsch. 2013. From Social Contact to Social Cohesion–The 7 Cs. *Music and Medicine* 5 (10 2013), 204–209. https://doi.org/10.1177/1943862113508588

Hideki Kozima, Marek Piotr Michalowski, and Cocoro Nakagawa. 2009. Keepon: A playful robot for research, therapy, and entertainment. *International Journal of Social Robotics* 1, 1 (January 2009), 3–18. https://doi.org/10.1007/s12369-008-0009-8

R. V. Krishna, B. S. Sathish, P. Ganesan, P. J. Babu, and R. Abilash. 2015. Design of voice and gesture controlled Quadcopter. In *2015 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)*. 1–6. https://doi.org/10.1109/ICIIECS.2015.7193152

Marc Lieser, Ulrich Schwanecke, and Jörg Berdux. 2020. EAVE: Emotional Aerial Vehicle Evaluator. In *INFORMATIK 2020 (Lecture Notes in Informatics, 307)*, Ralf H. Reussner, Anne Koziolek, and Robert Heinrich (Eds.). Köllen, Bonn. To appear.

Marc Lieser, Henning Tjaden, Robert Brylka, Lasse Löffler, and Ulrich Schwanecke. 2017. A low-cost mobile infrastructure for compact aerial robots under supervision. In *2017 European Conference on Mobile Robots (ECMR)*. 1–6. https://doi.org/10.1109/ECMR.2017.8098678

Sergei Lupashin, Markus Hehn, Mark W Mueller, Angela P Schoellig, Michael Sherback, and Raffaello D'Andrea. 2014. A platform for aerial robotics research and demonstration: The Flying Machine Arena. *Mechatronics* 24 (2014), 41–54. Issue 1. https://doi.org/10.1016/j.mechatronics.2013.11.006

Daniel Mellinger and Vijay Kumar. 2011. Minimum snap trajectory generation and control for quadrotors. In *2011 IEEE International Conference on Robotics and Automation (ICRA '11)*. 2520–2525. https://doi.org/10.1109/ICRA.2011.5980409

Nathan Michael, D. Mellinger, Q. Lindsey, and V. Kumar. 2010. The GRASP Multiple Micro-UAV Testbed. *Robotics Automation Magazine, IEEE* 17, 3 (Sept 2010), 56–65. https://doi.org/10.1109/MRA.2010.937855

Jawad Nagi, Alessandro Giusti, Gianni A. Di Caro, and Luca M. Gambardella. 2014. Human Control of UAVs Using Face Pose Estimates and Hand Gestures. In *Proceedings of the 2014 ACM/IEEE International Conference on Human-Robot Interaction* (Bielefeld, Germany) *(HRI '14)*. 252–253. https://doi.org/10.1145/2559636.2559833

Tayyab Naseer, Jürgen Sturm, and Daniel Cremers. 2013. FollowMe: Person following and gesture recognition with a quadrocopter. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. 624–630. https://doi.org/10.1109/IROS.2013.6696416

Wai Shan Ng and Ehud Sharlin. 2011. Collocated interaction with flying robots. In *IEEE International Workshop on Robot and Human Communication (2011 RO-MAN)*. 143–149. https://doi.org/10.1109/ROMAN.2011.6005280

Sujit Rajappa, Heinrich Bülthoff, and Paolo Stegagno. 2017. Design and implementation of a novel architecture for physical human-UAV interaction. *The International Journal of Robotics Research* 36, 5-7 (2017), 800–819. https://doi.org/10.1177/0278364917708038

Angela Schöllig, Federico Augugliaro, Sergei Lupashin, and Raffaello D'Andrea. 2010. Synchronizing the motion of a quadrocopter to music. In *2010 IEEE International Conference on Robotics and Automation*. 3355–3360. https://doi.org/10.1109/ROBOT.2010.5509755

Megha Sharma, Dale Hildebrandt, Gem Newman, James E. Young, and Rasit Eskicioglu. 2013. Communicating affect via flight path Exploring use of the Laban Effort System for designing affective locomotion paths. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*. 293–300. https://doi.org/10.1109/HRI.2013.6483602

Ramon A. Suárez Fernández, Jose Luis Sanchez-Lopez, Carlos Sampedro, Hriday Bavle, Martin Molina, and Pascual Campoy. 2016. Natural user interfaces for human-drone multi-modal interaction. In *2016 International Conference on Unmanned Aircraft Systems (ICUAS)*. 1013–1022. https://doi.org/10.1109/ICUAS.2016.7502665

Henning Tjaden. 2019. *Robust Monocular Pose Estimation of Rigid 3D Objects in Real-Time.* Ph.D. Dissertation. Johannes Gutenberg University Mainz, Germany. https://nbn-resolving.org/urn:nbn:de:hebis:77-diss-1000025478. Retrieved: 2021-01-14.

Michael L. Walters, Kerstin Dautenhahn, Kheng Lee Koay, Christina Kaouri, René te Boekhorst, Chrystopher Nehaniv, Iain Werry, and David Lee. 2005. Close encounters: spatial distances between people and a robot of mechanistic appearance. In *5th IEEE-RAS International Conference on Humanoid Robots, 2005.* 450–455. https://doi.org/10.1109/ICHR.2005.1573608

Alexander Yeh, Photchara Ratsamee, Kiyoshi Kiyokawa, Yuki Uranishi, Tomohiro Mashita, Haruo Takemura, Morten Fjeld, and Mohammad Obaid. 2017. Exploring Proxemics for Human-Drone Interaction. In *Proceedings of the 5th International Conference on Human Agent Interaction* (Bielefeld, Germany) *(HAI '17)*. 81–88. https://doi.org/10.1145/3125739.3125773