Kinetic Scrolling-based Position Mapping for Haptic Teleoperation of Unmanned Aerial Vehicles

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Abstract—In this paper, we present a haptic teleoperation control algorithm for unmanned aerial vehicles, applying a kinetic scrolling-based position mapping. The proposed algorithm overcomes the master workspace limitations and enables to teleoperate the aerial vehicle in unbounded workspace in a fast and intuitive manner. Moreover, it provides high precision to teleoperation tasks. Simulation and experimental results validating the applicability and effectiveness of the proposed algorithm are also presented.

I. INTRODUCTION

The remote control of unmanned aerial vehicles (UAVs) represents a challenging task, which in general requires experience of the pilot. Thus, in the recent past, progress has been made in developing autonomous UAVs for various applications, e.g. [1]–[3]. Nevertheless, there are still applications where a fully autonomous behaviour is not possible or desirable, such as air surveillance, rescue missions or inspection, which require human reasoning or supervision to be successfully accomplished. As in the scope of the European project AIRobots [4], within which this work was accomplished, the main objective is to develop an aerial inspection robot that actively interacts with its surrounding under the supervision of a human operator. While the operator stays in the control loop and is responsible for high level tasks, the operator should not be concerned with low level control such as the stabilization of the avionic system.

In the field of semi-autonomous robotics, haptic teleoperation has proved its great potential and benefit of providing major environmental awareness to a human operator while enabling high control accuracy, such as in the field of surgical robotics or traditional robotic manipulators [5], [6]. Consequently, several research groups recently started to investigate the application of haptic teleoperation to aerial vehicles. In [7]–[9], a theoretical and experimental investigation of the use of wave variables for a collision-avoidance system for UAVs is presented. The feedback force is calculated based on an artificial force-field. In [10], [11], the authors propose the use of an admittance control framework for haptic teleoperation of UAVs. Furthermore, they introduced the concept of optical impedance to provide a haptic feedback for obstacle avoidance. They provided simulation and experimental results of controlling the altitude of a quadrotor. In earlier work, we presented an approach, which is based on an energy consideration and makes use of the concepts of network theory and port-Hamiltonian systems, to provide the human operator with a sensitive cognition of the environment. Lee et al. [12] proposed a haptic teleoperation to control multiple UAVs over the internet.

To control the UAVs position, the aerial vehicle is usually equipped with an on-board position or velocity controller. Accordingly, the input consists of a corresponding references and a desired heading angle. In classical haptic teleoperation, where the haptic device is typically a replica of the slave device, and thus disposes similar kinematics, a direct or scaled mapping of the masters position to the slaves is common. However, due to the dissimilarities between the kinematics of an aerial vehicle and of a haptic device, a direct mapping is usually not feasible. Moreover, the workspace of a haptic device is limited and quite small compared to the UAVs, which is essentially infinite and unbounded. In order to overcome these limitations, the commonly used approach is to map the displacement of the haptic device to a reference velocity of the UAV [8], [12], [13]. This mapping method causes a trade-off between achievable precision and workspace during haptic teleoperation.

This paper proposes a haptic teleoperation algorithm for aerial vehicles to overcome the workspace limitations of the haptic device by providing high task precision. The approach is inspired by kinetic scrolling and is validated in both simulation and experiments.

II. HAPTIC TELEOPERATION WITH A KINETIC SCROLLING-BASED POSITION MAPPING

The main functional blocks of a typical haptic teleoperation control structure of UAVs are shown in Fig. 1. The master system consists of the haptic interface (master device) and the master controller. The slave system consists of the teleoperated UAV (slave system) and its controller. The two systems exchange relevant signals through the communication channel.

The interaction of the operator with the slave device through the haptic interface is bilateral, i.e. the human operator, besides commanding the slave system, receives a force feedback through the haptic device that depends on the response of the slave to his command. It is the task of the master controller to generate the force feedback that is displayed on the master device. Besides, it maps the operators inputs to the corresponding references of the slave device. On the other side, the slave controller ensures that the
slave is following the reference signal. Note that, though the communication channel is typically unreliable and introduces various imperfection, they are not considered in this work.

A. Kinetic Scrolling-based Position Mapping

In this section, we describe a new approach to overcome the limitation of the workspace on the master side, based on kinetic scrolling [14], [15]. Kinetic scrolling became standard on modern smartphones, where the user can interact with it in a natural and intuitive manner. This inspired the mapping of the operators inputs to the reference signal of the slave device of the teleoperation control loop proposed.

1) Core Idea: The mapping algorithm is divided into two modes, namely a direct and a sliding mode. In the direct mode, a proportional mapping of the masters position to the slaves reference position is proposed. Whereas in the sliding mode, the operator is provided with the possibility to slide the reference position away. This sliding is decelerated automatically similar to the kinetic scrolling on smartphones. The amount of the sliding is influenced by the users speed in the direct mode before switching to the sliding mode. Note that, in both modes a reference position is transmitted to the onboard position controller of the aerial vehicle.

2) Mathematical Description: To realize the proposed mapping algorithm, a virtual point mass \( m_v \) is introduced. In the direct mode, the virtual mass is coupled with the master device by a spring and damper. Whereas in the sliding mode, the virtual mass is decoupled from the master device. To decelerate and eventually bring the virtual mass to rest in sliding mode, a viscous damping is also introduced in the system. Moreover, the coupling spring is made to have variable rest length \( x_0 \). As such the desired offset between the virtual mass and the master device, when switching back to direct mode, can be maintained. Fig. 2 shows the physical model of the core idea. Note that the virtual mass system is implemented in the master controller.

In the proposed mapping, the operator is in charge of the switching between the two modes, e.g. through a button on the haptic device. Note that, in both modes, it is the position \( x_v \) of the virtual mass that is proportionally mapped to reference position of the slave device \( x^* \).

According to the principle of linear momentum, the following equation of motion holds for the virtual point-mass:

\[
\begin{align*}
    m_v \ddot{x}_v &= -k_v (\Delta x - x_0) - d_v \dot{x}_v \quad &\text{(direct mode)} \\
    &- d_v \dot{x}_v \quad &\text{(sliding mode)}
\end{align*}
\]  

where \( x_m, x_v \in \mathbb{R}^3 \) represent the positions of the master device and the virtual mass respectively, \( m_v \) denotes its mass, \( \Delta x = x_v - x_m \), \( d_v \) and \( k_v \) are the coefficients of the coupling damper and spring, \( d_v \) is the coefficient of the viscous friction that is implemented in sliding mode.

During the sliding phase, the virtual viscous damping ensures that the virtual mass eventually stops. Note that, from Eq. (1), the position of the virtual mass in sliding mode is:

\[
x_v(t) = \frac{v_0}{d_c} (1 - e^{-\frac{t}{d_c}}), \quad \text{with } d_c = \frac{d_v}{m_v}.
\]  

where \( v_0 \) denotes the initial velocity, i.e. the velocity just before the virtual mass is decoupled. As shown in Eq. (2), the human operator can directly influence the direction and amount of the sliding with his motion before switching to the sliding mode, i.e. the faster the user moves the haptic device, the further the virtual mass slides. In contrary, the virtual mass does not slide if the initial velocity is zero.

As can be seen in Eq. (1)-(2), the parameters \( k_v, d_v, m_v \) and \( d_v \) influence the mapping of the haptic inputs to the reference position. To ensure higher performance during the direct mode, \( k_v \) has to be high enough. Besides, \( m_v \) should be low so as to minimize the inertia the user feels during teleoperation. Moreover, \( d_v \) has to tuned based on \( m_v \) and \( k_v \) so that the unintended oscillatory motions are avoided. Once the above parameters are chosen, \( d_v \) can be set based on the amount of sliding desired by the task. For instance, higher value of \( d_v \) decelerates the virtual mass quickly.

Eventually, the position of the virtual mass \( x_v \) is mapped to the reference position of the slave device \( x^*_s \) as

\[
x^*_s = \alpha \cdot x_v,
\]  

where \( \alpha \) represents the scaling factor.
B. Force Feedback
The master device is capable of displaying force feedback, which is generated by the master controller. We propose a force feedback only in the direct mode, i.e., when the haptic interface actively influences the slave device. This feedback force depends on the deviation of the actual position of the slave from the reference. As such, the operator gets a haptic cue that provides information about the slave’s reaction to his stimulations as well as to external disturbances \( F_E \).

The displayed force is proportional to the difference between the commanded and actual slave position, which gives an indication of the magnitude and direction of the positional deviation. The force feedback vector is:

\[
F_F = -\beta(x^*_s - x_s),
\]  

where \( \beta \) denotes the force scaling factor.

C. Stability Consideration
The stability of a control system is a crucial factor for the success of the operation. Hence, in this section, we present some important consideration concerning the overall stability of the proposed teleoperation algorithm.

The complete control loop of the haptic teleoperation is shown in Fig. 3. As can be seen, the UAV is endowed with a trajectory/stabilization flight controller. For this purpose, typically, a cascaded control strategy is adopted, where the UAV's rotational dynamics are treated separately from its translational ones, e.g. [2], [3], [16]. Such an approach is usually feasible, given the two sets of dynamics are time-scale separated. Various authors have shown that the stability of the UAV is ensured by applying two cascaded controllers.

![Fig. 3: Cascaded control structure of the proposed haptic teleoperation.](image)

Following similar line of reasoning, again under the assumption that the additional cascaded loop is time scale separated, we can separately treat the stability of this loop, i.e the master system. For ease of illustration, the stability analysis presented in this section is for 1D, as it is always possible to decouple each DoFs of the fully actuated haptic interface by applying an appropriate controller. As such, the haptic interface is modelled as a mass-damper system.

The switching dynamics of the master system is given by

\[
\begin{align*}
\dot{x}_m &= F_h - d_m \dot{x}_m + k_c(\Delta x - x_0) + d_c \Delta \dot{x} + F_F \\
\dot{\Delta} &= 0
\end{align*}
\]  

in direct mode (\( \lambda = 0 \)) and, in sliding mode (\( \lambda = 0 \)), by

\[
\begin{align*}
\dot{x}_m &= F_h - d_m \dot{x}_m \\
\dot{\Delta} &= -k_c(\Delta x - x_0) - d_c \Delta \dot{x} \\
\dot{x}_0 &= \Delta \dot{x}
\end{align*}
\]  

where \( F_h \) and \( x_s \) are the force input applied by the user and the position of the UAV. Both are inputs to the outer cascaded loop, while \( x^*_s \) given in Eq. 3 is the output.

If we consider \( x = [x_m, \dot{x}_m, \dot{x}_v, x_v, \dot{x}_o] \) as states of the system, the system matrices of the switching system are:

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
0 & \frac{1}{m_m} \lambda k_c & 0 & 0 & 0 \\
\frac{\lambda d_c}{m_m} & 0 & \frac{\lambda(k_c - \alpha)}{m_m} & 0 & \frac{\lambda d_c}{m_m} \\
0 & 0 & 0 & 0 & 0 \\
0 & -\lambda & 0 & \lambda & 0 \\
0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

where \( d_m \) denotes the coefficient of the intrinsic viscous friction of the haptic device and \( \delta = \lambda d_c + (1 - \lambda)d_v \).

For the above system to be bounded input bounded output stable, it is necessary that the system matrix \( A_i \), for \( i = 1, 2 \) are Hurwitz. In the sliding mode, the characteristic polynomial \( P(s|\lambda = 1) \) of the system is given by \( (a_5 = 1) \)

\[
s^5 + \left( \frac{d_v}{m_v} + \frac{m_d}{m_v} \right) s^4 + \left( \frac{d_v m_d}{m_v m_v} \right) s^3 = a_{4} = a_{3}
\]

Based on Routh-Hurwitz stability criterion, it is rather straightforward to see that the system is stable in this mode since all coefficients are positive.

In the direct mode, the characteristic polynomial \( P(s|\lambda = 0) \) is given by \( (a_5 = 1) \)

\[
\begin{align*}
s^5 + \left( \frac{m_v d_e + m_e (d_m + d_e)}{m_v m_v} \right) s^4 + \left( \frac{k_c (m_v m_e + d_m d_e)}{m_v m_v} \right) s^3 \\
+ \left( \frac{d_m k_c + \beta \alpha d_e}{m_v m_v} \right) s^2 + \left( \frac{\beta \alpha k_c}{m_v m_v} \right) s
\end{align*}
\]

Again according to the Routh-Hurwitz stability criterion, the system is stable if \( a_{1,5} > 0, a_4 a_1 > a_2 \) and \( a_4 a_2 a_1 > a_3^2 + a_2^2 \). Due to space limitation, we don’t present detailed mathematical expressions as to what the range of values of each parameters should be to fulfill the above requirements. However, brief qualitative explanations are provided.

The first requirement is always fulfilled since the coefficients of the system are positive. The second and third requirements are not violated unless the value of \( \beta \alpha d_e m_v m_v \) extremely large, which is not usually the case since \( m_v \) is in order of \( 10^{-1} \) and the value of \( \beta \) is limited by the maximum force displaying capability of the master device.

Once the parameters are tuned such that \( A_i \) is Hurwitz, stability of the switched signal with arbitrary switching signal boils down to finding a common Lyapunov function \( V(x) = x^T P x \), where \( P = P^T > 0 \). This problem has been reformulated as a convex optimization problem of checking whether the linear matrix inequality (LMI) \( A^T P + PA < 0 \) is feasible. It has been verified through extensive computation that the above LMI is feasible. Hence, the proposed haptic teleoperation algorithm does not introduce any instabilities into the flight control loop in either mode, given the cascaded control loops are time-scale separated.
Fig. 4: Simulation results of the haptic teleoperation with the kinetic scrolling-based position mapping. Note, that the vertical dashed lines in the first four plots indicate the switching between the two modes.

III. SIMULATION RESULTS

In this section, simulation results that validate the proposed algorithm are presented. In addition, simulation results that show the effect of the different variables on the proposed mapping strategy are provided. The slave system is modeled as a point mass with a PD controller. During the simulations, a direct user command has been recorded and force feedback has been displayed using a Omega6 haptic device.

Fig. 4 shows the results of the first simulation. The top plot shows the position of the master device. As it can be seen from the second plot, the movement of the virtual mass is coupled with the master when in direct mode, i.e. when the switching signal is zero (see the bottom plot). In the sliding mode, the virtual mass is decoupled from the master device and slides away from it and eventually comes to rest (see the second plot b/n 28 – 38 sec). As illustrated in the plot, for a given viscous friction \( d_c = 0.1 \) the amount of sliding depends on the velocity that the virtual mass acquires just before decoupling. The slave device follows the scaled trajectory \( (\alpha = 2) \) of the virtual mass. It is shown in the fourth plot that the rest length of coupling spring changes according to the position difference between the master and the virtual mass when it is in the sliding mode. As such, it serves as the desired position offset between the master and the virtual slave in the direct mode. It is also worth to note from the second plot that the user can abort the sliding mode, bringing the UAV to a complete stop, or be extended to a larger motion, covering larger distances. The third plots shows the force feedback displayed to the operator through the haptic device. The force feedback depends both in magnitude and direction on the deviation of the position virtual mass, which is almost the same as the position command from the user, and the UAV. In the sliding mode, this force feedback is turned off, enabling the user to reset the position of the master device.

To demonstrate the effects of the parameters of the various variables on the proposed algorithm, extensive simulations have been carried out. Fig. 5 shows the effect of the damping coefficient \( d_c \) of the virtual mass. The same user input as in the previous simulation has been used. As can be seen from the figure, the higher the damping coefficient, the lower the position covered during the sliding mode becomes. This agrees with our expectation and Eq. 2.

Similar simulations have been done to demonstrate the effect of the stiffness of the coupling spring \( k_c \) and the virtual mass \( m_v \). Fig. 6 shows that increasing \( k_c \) and \( m_v \) gives similar characteristics. Though, we choose to present their characteristics using the same plot: while increasing \( m_v \) helps to cover larger distances in sliding mode once it acquires higher momentum, its higher inertia is felt by the user in the direct mode. As a consequence, it may compromise the fidelity of the force feedback since the additional inertia effect of the virtual mass is also present. On the other hand, the effect of \( k_c \) is primarily observed in the direct mode. It improves the position coupling between the master and the virtual mass only if accompanied by appropriately tuned \( d_c \).
Otherwise, it may result in highly oscillatory motion.

The above simulation results demonstrate the applicability of the proposed algorithm that enables haptic telecontrol of UAVs flying in a large workspace using a haptic device that has limited workspace. They also provide general guidelines on how to tune the parameters of the control variables so as to obtain a better results for the desired task.

IV. EXPERIMENTS

A. Experimental Set-up

The flight experiments were conducted in an indoor test area (size about 4.00m × 3.75m × 2.75m). Fig. 7 shows the complete system overview of the experimental setup. Each component of the system are briefly described hereunder.

1) Aerial Vehicle: The aerial platform, i.e., the slave device, is the AscTec Pelican quadrotor. The helicopter is provided with a Flight Control Unit (FCU), i.e., all on-board sensors plus two ARM7 microprocessors.

2) Haptic Device: The Force Dimension Omega.6 haptic device is used as a master system. This device provides translation as well as rotation sensing with high accuracy, and it is featured with a precise gravity compensation to enable accurate haptic transparency. The provided Force Dimension SDK is used as a software interface to the device. The button on the top of the Omega.6 is used to send a signal to switch between the two proposed mapping modes.

3) External Positioning System: As an external positioning system a PTV Phoenix VisualEyez VZ 4000 tracker unit is used. The tracker captures the motion of the active markers (LED), mounted on the UAV, and estimates the UAV’s pose.

4) Ground Station: Both the on-board Atom processor board and the ground station computer are equipped with a Ubuntu Linux 10.10. The ground station executes the master side of the teleoperation algorithm and it runs the Robot Operating System (ROS) master. On-board, a ROS interface runs on the Atom board. Besides, the position and attitude controller of the UAV are executed on the FCU. As a position controller, a PID controller with a feedthrough term is implemented [3]. The attitude controller is a PD algorithm provided by AscTec. The aerial vehicle communicates with the ground station over a WiFi data link.

B. Experimental Results

In the first experiment, all translational degrees of freedom of the UAV are controlled by the user. The first plot of Fig. 8 shows the positions of the tip of the haptic interface. In Fig. 9 it can be seen that the virtual mass moves together with the master device, when in direct mode, i.e. the switching signal \( \lambda = 0 \) (see the last plot of Fig. 8). The UAV follows the virtual mass’s trajectory with a certain delay due to its dynamics. The force displayed to the user is depicted in the second plot of Fig. 8. Note that during the sliding mode, the motion of the master device does not influence the motion of the virtual mass. However, to enable the coupling of the master and the virtual mass when switching back to the direct mode, while keeping the desired offset, the rest length of the coupling spring changes in the sliding mode (see the third plot of Fig. 8). The user is able to teleoperate the UAV in both modes and the sliding is possible in multiple directions.

Though testing the robustness of the algorithm to various network induced imperfections, e.g., time varying delays and packet loses, is not the intent of this paper, an additional experiment was performed. This experiment in an inter-country experiment, where the human operator and the aerial vehicle were geographically separated and communicated through a standard internet connection. The master side, including the operator, were located at the University of Twente/Netherlands, whereas the UAV and its controller were flying at the ETH Zürich/Switzerland. During this experiment, a quadrotor developed by ETHZ, equipped with an AscTec FCU and dedicated position controller, was used. A
Vicon system was used as an external positioning system. For environmental awareness, the human operator was provided with a video stream from an off-board camera. The attached video to this paper shows the performed experiment.

Fig. 10 shows an excerpt of the results of the experiment, where the operator controlled all three translational degrees of freedom. The heading was kept constant during the experiment. As can be seen, also in these experiments the trajectories produced by the sliding of the virtual point-mass are smooth, and are accurately tracked by the slave controller.

V. CONCLUSIONS

The mapping algorithm, proposed in this work, offers high precision for teleoperation tasks. Furthermore, it allows the human operator to overcome the workspace limitation of the haptic device and cover large distances in the unbounded workspace of the slave device in a fast and intuitive manner. The haptic teleoperation controller with a kinetic scrolling-based position mapping was successfully implemented and experimentally tested with two different setups.

![Image of the experimental setup](image)

**Fig. 7: Overview of the experimental setup**

**Fig. 10: Inter-country experimental result: reference and current position of the UAV, the force feedback and switching signal**

**REFERENCES**


