Admittance mode framework for haptic teleoperation of hovering vehicles with unlimited workspace

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Abstract

This paper discusses a new approach to haptic feedback for teleoperation of hovering vehicles. Traditionally airplane and helicopter controls use the displacement of a joystick as the main supervisory control input. It is common to overlay force feedback to convey additional information about *forces* occuring in the controlled craft. However, there are some fundamental problems when trying to feed back information about obstacles, position, velocity or inertia of the craft in this mode of control. This paper proposes to use an admittance control mode for flying a hovering vehicle such as a quad-rotor, which enables a more direct mapping from vehicle position to haptic feedback. Furthermore it is discussed how to overcome the problem of controlling a vehicle with unlimited workspace from a haptic joystick with limited workspace in admittance mode. Experiments were performed in a virtual 3D simulation to evaluate the feasibility of admittance control with position feedback, and to compare two different types of admittance mode feedback with impedance mode feedback.

1 Introduction

Teleoperation of remote robotic devices has been a core research topic within robotic communities for decades, and it has been widely used for various applications in industry [Tang *et al.*, 2009], military [Kron *et al.*, 2004], search & rescue [Ohno *et al.*, 2010], exploration [Penin *et al.*, 2000], surgery [Tobergte *et al.*, 2009], etc. Teleoperation of robotic ground vehicles, underwater vehicles and aerial vehicles poses the additional challenges of unbounded workspace and significant dynamics to the robustness and stability challenges of classical teleoperation of robotic manipulators. To the authors knowledge, most existing teleoperative environments for aerial robotic vehicles are based on a supervisory control framework with primarily vision, audio and measurement data streams fed back to the remote pilot who controls the vehicle by setting way points for the onboard vehicle control to track. In more recent work, force feedback control has received more and more attention. The limits of performance for force feedback teleoperation are investigated in [Daniel and McAree, 1998][Chen *et al.*, 2007]. Haptic interfaces have also been considered for assisting control of aerial vehicles [Boschloo *et al.*, 2004][Lam *et al.*, 2009].

Controlling a hovering vehicle such as helicopters or quadrotor craft is challenging, as these vehicles holonomically move along 3 translational degrees of freedom and one rotational degree of freedom. This means that the direction of travel and the direction of vision (i.e. forward-pointing camera) do not necessarily coincide. This is different from nonholonomic vehicles such as cars and aeroplanes, which essentially move along one translational degree of freedom (which is usually identical with the direction of vision) while controlling one or two rotational degrees of freedom to point the vehicle towards the desired goal. Controlling lateral and vertical velocity is therefore a potentially challenging additional task when flying holonomic hovering vehicles.

The scope of the authors' work is to provide haptic feedback to the pilot of a hovering aircraft that conveys the vehicle's velocity and potential collisions with nearby obstacles, to allow the pilot to accurately position the vehicle close to structures for e.g. visual inspection tasks of buildings. When using spherical optic flow as a sensor input, it is possible to avoid collisions with obstacles by feeding back a *virtual viscosity* force to the vehicle, a force that is proportional to measurements derived from spherical optic flow (such as divergence in the focus of expansion [Schill *et al.*, 2009]). As optic flow is inversely proportional to the distance of objects this leads to higher viscosity close to objects, requiring increasing amounts of force to move closer. Additional forces derived from *equatorial flow* can be used for corridor centring. This approach has been demonstrated previously with closed loop haptic feedback in a simulation [Mahony *et al.*, 2009] and on a ground based robot in [Schill *et al.*, 2008]. In this previous work the joystick displacement (controlled by the operator) was used as the control input for the vehicle, and the forces derived from optic flow were fed back to the vehi-

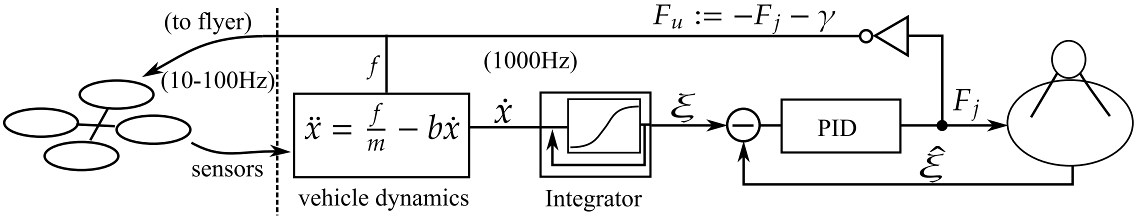

Figure 1: Admittance control framework

cle and mirrored to the haptic device (impedance mode). This led to two closed control loops that slowed the vehicle down when approaching obstacles, one directly on the vehicle, and an outer loop through the joystick itself, i.e. the forces applied to the joystick moved the joystick in such a way that the changed joystick position also slowed the vehicle down. While this system successfully avoided collisions and therefore made vehicle control safer, the feedback perceived by the pilot was unintuitive. The vehicle itself was exposed to virtual viscosity forces, which were mapped directly to the joystick as a force, but the joystick *position* was mapped to an acceleration *force* on the vehicle, which created a mismatch of domains. In practice this meant that the user did not perceive viscosity when approaching an obstacle, but rather felt the joystick actively pushing backwards across the center position to achieve deceleration. Additionally, when approaching a wall, the system would find an equilibrium where the vehicle was slowing down such that measured divergence stayed constant with decreasing distance, leading to a constant force perceived by the user, irrespectively of actual distance.

This paper proposes a new framework for haptic teleoperation of hovering vehicles that addresses the domain mismatch and provides a more direct, intuitive mapping between vehicle and joystick which is more suitable for feeding back vehicle position, velocity, and potential collisions. In Section 2 and 3, backgrounds of feedback control methods, signal mapping and technical issues of controller implementation are introduced. In Section 4, experiments in a virtual environment are conducted to test the accuracy, speed and other performances of the proposed system. Concluding remarks and future work will be given in Section 7.

2 Admittance control

In haptics, the admittance control mode is a dual to impedance control. In impedance control, the user applies a displacement to the joystick (which is usually very lightweight and has low friction), and the joystick responds with a force (e.g. when it reaches a virtual obstacle). In admittance control the user applies a force to the joystick, and the joystick responds with an appropriate displacement. Cause and effect are therefore reversed between the two modes. Typically admittance mode is used to achieve higher forces and better stiffness by mechanical means. For the work presented here admittance mode is used to address the domain mismatch described above, and to enable more intuitive feedback of vehicle properties. We are using the Novint Falcon in an emulated admittance mode, by implementing a high-gain position control loop to achieve (limited) rigidity. By changing the input to this high-gain position controller it is possible to move the end effector to different positions, (almost) regardless of user input. The Novint Falcon is designed as an impedance device, which means that this emulation of admittance mode still has limited force and rigidity. It is possible to achieve better rigidity with impedance devices by using analog feedback circuitry [Wilson and Niemeyer, 2009].

To measure the force that the user applies to the rigid end effector, the output of the high gain position controller is inverted (the output forces required to keep the joystick rigidly in position are approximately identical to the disturbance forces externally applied by the user). The desired joystick displacement is denoted as $\xi(t)$, the measured (actual) displacement is $\hat{\xi}(t)$. The high gain controller computes a force F_j that is fed to the joystick motors to move and keep the end effector rigidly on the set position ξ. The "force output" of the emulated admittance device (i.e. the measured force that the user applies to the end effector) is $F_u(t) := -(F_j(t) - \gamma)$, where γ is a bias compensation term to compensate for gravity acting on the end effector (Figure 1)

Instead of using joystick *displacement* to control a hovering vehicle, it is now possible to use the *force* $F_u(t)$ that the user applies to the joystick as a control input to the vehicle. In the example of an electronically stabilised, self-leveling quadrotor (such as the Ascending Hummingbird used by the authors) the control input for X and Y is mapped to an absolute tilt angle which is actively controlled by the onboard stabiliser. The control input for Z is mapped to total thrust. By finding the correct offset for thrust to reach the hover point at the "zero" stick position, it can be assumed for small tilt angles that the forces applied to the joystick are proportional to the forces that the rotors apply to the vehicle. For larger tilt angles it is possible to achieve a better approximation by explictly calculating the resulting thrust vector and applying compensation to the control forces.

A test was performed to verify that it is possible to control a quadrotor vehicle using admittance mode as described on the low-cost Novint Falcon. The 3D forces applied by the operator to the joystick $F_u(t)$ (approximated as described above) were sent to the quadrotor via a commercial R/C remote control. It was easily possible to fly the quadrotor by applying forces to the Novint Falcon, which in this test did not change its set position. The control was perceived as very direct and responsive by the pilot. As the joystick did not have to move over larger distances across its workspace, any magnitude of possible control input could quickly be achieved, resulting in fast, low-lag control. The vehicle was successfully flown in constrained indoor environments with an accuracy comparable to traditional precision remote controls as used by R/C pilots. The pilot was able to apply large acceleration and deceleration forces quickly and accurately to move and quickly stop the vehicle, and stable, accurate hover within 10-20 cm was achieved with ease.

There are multiple possibilities how to feed back vehicle properties to the pilot. In a traditional admittance framework the position of the robot would be used (with scaling) as the set position for the joystick, $\xi(t)$. This leads to a system where the user applies a force to the (initially rigid) joystick, which in turn accelerates the vehicle, and the resulting change in the vehicle's position moves the joystick accordingly. It is obvious that now force is mapped to force, and position is mapped to position, avoiding the domain mismatch described above. The user feels a direct representation of the vehicle's inertia, velocity and position. It is also obvious that if the vehicle stops due to a collision, or slows down due to obstacle avoidance mechanisms (such as the virtual viscosity concept described above), the user will be able to feel the effects transparently, as if moving the vehicle itself directly. It is now possible to implement arbitrary collision avoidance or guidance mechanisms (virtual rails, magnetic snaps, etc.) on the vehicle itself, while everything is mapped transparently to the haptic system without further changes. It is noteworthy that in the described admittance scheme, the system is effectively open loop with regard to position control if the user does not touch the joystick. This is different to the impedance scheme explored previously which maintains closed loop control through the joystick in the absence of an operator. However, the operator effectively "closes the loop" by holding the joystick grip: if a disturbance moves the vehicle from the desired position, the joystick will move accordingly, subsequently pushing against the operator's hand. If the operator does not move, this will apply an opposing force to the joystick, which will be sent to the vehicle and move the vehicle back to the desired position. Although the cause and effect are reversed, this will appear to the operator as if the vehicle was performing closed-loop position servoing according to the provided joystick position. The difference however is that the operator receives feedback with regard to the vehicle's progress, i.e. it is not possible to move the "set position" faster than the vehicle can keep up with.

This type of admittance control is well-known to the haptics community and is used in a number of systems (although not on flying vehicles to the authors' knowledge). The fundamental problem when applying this approach to a hovering robot is that the workspace of the robot is unlimited, while the workspace of the haptic device is limited. A possible solution to this problem is to build a haptic device with unlimited workspace (e.g. a 3D haptic trackball as currently under development by the authors). In this paper we describe a different solution which can be used on traditional haptic devices, which overcomes the workspace limitation while trying to maintain the tranparent, direct feedback of admittance control.

3 Problem Formulation

This section presents the basic problem formulation for the scenario considered and presents two feedback modes suitable for unlimited workspace robots. We assume that our system consists of a (simplified) hovering vehicle operating in an unlimited workspace, which is controlled in translation by linear 3D acceleration forces (for the sake of this analysis yaw, pitch and roll rotations are ignored and left for future publications). The operator controls the vehicle by applying forces to an admittance haptic device with three linear degrees of freedom with a limited workspace. The goal is to allow the operator to move and position the vehicle while receiving feedback (as transparently as possible) about the vehicle's movement.

The simplified vehicle dynamics is defined as in Equation 1, where $\ddot{x}$ is the acceleration, $\dot{x}$ is the vehicle velocity, f is the force input applied to the robot, m is the mass of the robot and b is the damping ratio (e.g. friction).

$$\ddot{x} = \frac{f}{m} - b\dot{x} \tag{1}$$

For a practical robotic quadrotor system the horizontal components of force f are controlled by specifying the desired inclination set point for the onboard attitude controller of the vehicle. The resulting component of the thrust force in the horizontal plane applies to the translational dynamics. The vertical force is generated by the total thrust vector, directly related to the set point for rotor speed. For simplification we assume that we can transform the control input f for a real vehicle into inclination set points and thrust set points with sufficient accuracy for practical purposes.

The quantity measured from the vehicle for haptic feedback purposes is the vehicle velocity $\dot{x}$. Measuring velocity for a practical system can be challenging. In this paper we will assume that velocity measurements are available. In a real system potential sensors to deliver velocity measurements are e.g. ranging devices such as the lightweight Hokyu laser range finder, doppler radar, optical flow in conjunction with a ranging device, or an external tracking system such as the VICON tracker, or GPS. Approximate velocity estimates can also be derived for short time spans by IMU integration, as small drifts are not relevant in the proposed framework.

In the admittance frame work we have a steady state model that decouples the force and position. The steady state displacement $\xi(t)$ is directly specified based on the signal received from the slave vehicle. The force F_u applied by the pilot is independent of the value of ξ. The dynamics of the joystick depend on the closed-loop dynamics of the inner control loop. The control force f applied to the vehicle can easily be derived from the user force F_u after scaling with a factor α:

$$f(t) := \alpha \cdot F_u(t) \tag{2}$$

Feeding back a quantity derived from the measured vehicle velocity $\dot{x}$ is somewhat less obvious due to the workspace limitations.

A first approach is to provide velocity feedback to the pilot, i.e. deriving the joystick set position ξ directly from velocity $\dot{x}$ (with scaling β_1):

$$\xi(t) := \beta_1 \cdot \dot{x}(t) \tag{3}$$

In this case the unlimited vehicle workspace does not matter. The maximum vehicle velocity is now bounded by the joystick workspace and the scaling factor (at least assuming that feedback shall be maintained), but this does not pose a problem. The pilot will not receive any position feedback, and will have to rely on other input (video, etc.) to accurately maintain position of the vehicle. Vehicle inertia will map to perceived viscosity of the joystick - if the pilot tries to command large accelerations, a resistive force will be perceived while the vehicle speeds up. Obstacles that cause the vehicle to stop will map to the joystick moving back to its center position.

A second approach is to provide position feedback while within a limited workspace area, and blend the feedback towards velocity feedback when traversing larger distances. This can be achieved by deriving a high-pass filtered position estimate from a leaky integrator, here defined in discrete time (ξ_m is the maximum allowed displacement of the joystick):

$$\xi(t) = \xi_m \tanh\left(\xi(t - \Delta_t) + \gamma \dot{x}(t - \Delta_t)\Delta_t\right) \tag{4}$$

This particular leaky integrator uses a sigmoid function tanh and was chosen for two reasons: a) the output is guaranteed to be within set limits while achieving smooth, gradual saturation instead of hard clipping, and b) the “leakiness” is larger for large displacements, moving the joystick away from its workspace limits more quickly, while maintaining approximate linearity close to the center of the workspace. In practice this means that if the vehicle reached a location of interest, the joystick will smoothly and slowly return to the center (slow enough to be almost imperceptible to the operator); after a brief settling time the operator can perform precision manoeuvering close to the center point of the joystick, while perceiving almost linear position feedback as in traditional admittance control.

Figure 2: The Novint Falcon Device (after modifications)

Both approaches provide closed loop control of the vehicle in conjunction with the operator (i.e. the operator closes the loop by holding the joystick). The first approach allows the operator to control the vehicle velocity, but no position feedback is transmitted. The second approach provides *relative* position feedback while approximately stationary, but provides non-linear velocity feedback when moving quickly. The joystick position is proportional to an equilibrium point between the losses of the leaky integrator, and the measured velocity input. As any possible velocity will be mapped within the workspace of the joystick, this framework does not impose any theoretical limits on the maximum velocity.

For comparison, a third mode was implemented using impedance control. A virtual centre spring is applied to the joystick, applying a proportional force towards the zero position. Inspired by the stiffness feedback presented in [Lam *et al.*, 2009] the spring constant of the virtual centre spring is proportional to the vehicle velocity. The control input to the vehicle is the force applied to the joystick (not the displacement). This mode effectively scales the magnitude of control force applied to the flyer by the velocity; i.e. a given stick displacement corresponds to a small force for low speeds, and a large force for large speeds. Due to the modulated spring stiffness the force perceived by the user varies accordingly. This scaling should help accurate positioning when going slow, while providing larger bandwidth when going fast. The perceivable effects of this mode are very subtle, and this mode can be considered very similar to no haptic feedback at all.

4 Experimental setup

To evaluate the feasibility of the proposed framework, we implemented a simulation based on the open source 3D game engine Irrlicht. To emulate an admittance device using the Novint Falcon, a high gain PID controller was implemented (settling time is approximately 0.1seconds after careful tuning).

Figure 3: The simulation environment. Left: The target (red) in the positioning task has to be aligned within the indicated frames (blue). Right: the path following task. Arrows indicate the direction, waypoints to pass are marked in green.

The simulation implements the simplified vehicle dynamics described in equation 1. The discrete dynamics simulation runs at 1000 Hz, the same speed as the haptics controller, using the input force $f := F_u$ from the admittance haptic device emulation. The calculated velocity is forwarded to the game engine, where the vehicle position is calculated. The game engine runs at 50-60 Hz, visualising the virtual world as seen by the simulated vehicle. The game engine also checks for collisions with walls and prevents the vehicle from flying through walls. The actual velocity after collision checking which is derived from the position calculated by the game engine is fed back to the faster vehicle dynamics simulation, where a simple P-controller applies a correcting force to the vehicle simulation to minimise the error between the estimated velocity in the dynamics simulation, and the actual velocity of the vehicle. Essentially this implements an observer, where the system model is driven by a feed-forward term (the input force), and kept in agreement with the measured velocity using a feedback loop. While not strictly necessary in the simulation, this method makes the framework more applicable to a real system where velocity measurements may be obtained at a low frequency of 20-50 Hz and with some time lag. The internal observer can run at a high frequency of 1000 Hz to give smooth and stable operation of the haptic subsystem, while staying close to the actual, true velocity of the system. It is also possible to apply additional sensor data measured at different sampling rates, such as actual accelerations measured by the IMU. The simulation achieves stable control of the flyer and the haptic subsystem, conveying feedback as expected for both velocity feedback, and for relative position feedback (using the leaky integrator according to equation 4).

Two experiments were carried out. The aim of the first experiment is to measure performance in a positioning task (motivated by an inspection scenario where the vehicle is used to obtain a steady image of a point of interest). Two square-shaped targets are marked on a wall within the 3D simulation, approximately 10 meters apart (290 units in the virtual world). The test subjects are instructed to fly the vehicle in front of the first target and stop in front of it, trying to maintain their position as accurately as possible. Visual feedback is facilitated by two superimposed centered frames of different size; the target has to be centered within the frames, and distance has to be maintained so that the outline of the target appears between the two frames (see figure 3). The vehicle position has to be maintained for 3 seconds within the indicated boundaries. After this period, an acoustic signal indicates success, and an arrow is overlayed as visual feedback indicating the direction to the other target. The subject then has to fly sideways in the indicated direction until reaching the second target, and repeat the positioning task as with the first target. After success, a third and last positioning task has to be carried out in front of the first target, after which the trial ends. Vehicle position and time stamps of start and end of each positioning task are logged for analysis.

The second experiment investigates following an approximate trajectory through cluttered environment. A path through the virtual world is indicated by a number of waypoints. Each waypoint is visualised by an arrow which points towards the next waypoint. The path follows corridors through the virtual world and includes some altitude changes and obstructions (following a ramp upwards, flying through doorways). In this experiment the yaw axis of the vehicle had to be controlled using two buttons on the Falcon device ("left" and "right"). The subjects are instructed to follow the path as quickly as possible while avoiding collisions with walls. Progress along the path is measured by checking proximity to the waypoints.

The experiments were carried out with thirteen subjects without prior exposure to the system. Each subject performed both tasks for three different modes of feedback: Mode A em-

Mode	completion	collisions	distance: mean/std. deviation	time: mean/std. deviation
A	6	12	6644 / 2367	60 / 14
B	11	4	4104 / 850	50 / 12
C	13	2	4263 / 1765	55 / 13

Figure 4: Path following: experimental results for 13 subjects

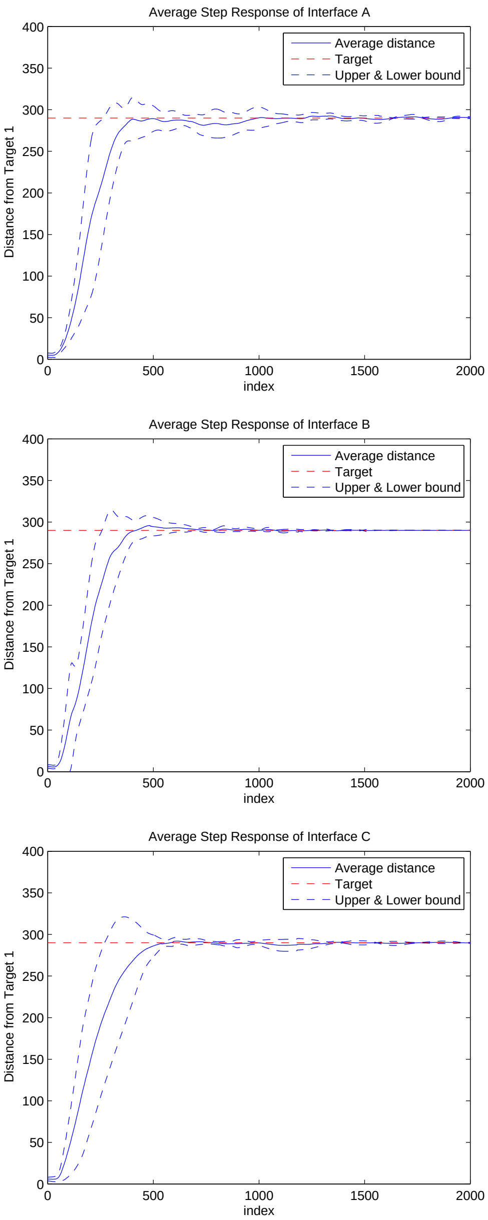

Figure 5: Results of the positioning user trials (average position and standard deviation). From top to bottom: Mode A used impedance mode with modulated spring stiffness; mode B applied relative position feedback according to equation 4; mode C used velocity feedback after equation 3. The plots show the distance to the target for all transitions and users.

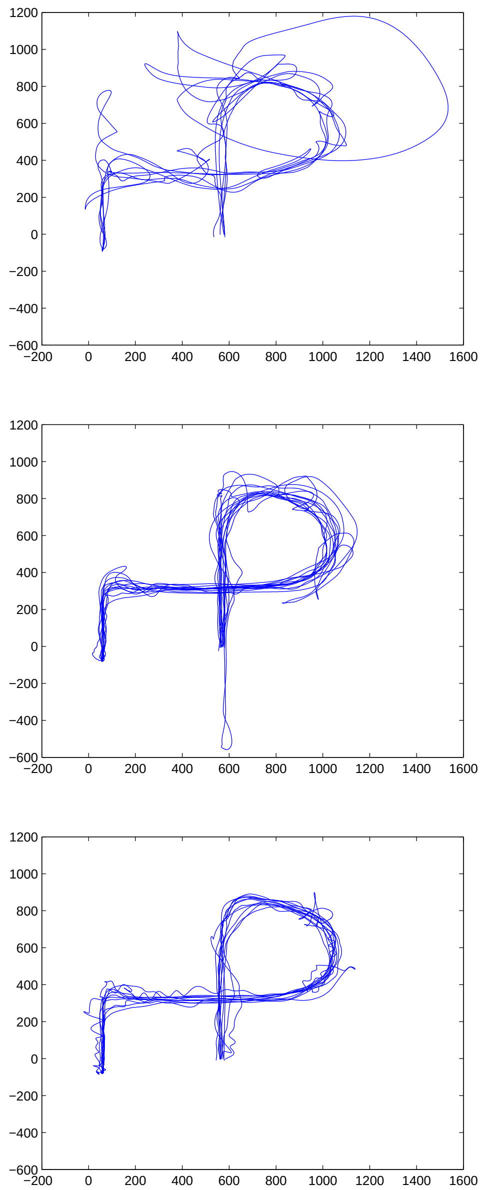

Figure 6: Results of the path following user trials. From top to bottom: Mode A used impedance mode with modulated spring stiffness; mode B applied relative position feedback according to equation 4; mode C used velocity feedback after equation 3. The plots show the paths taken by all subjects.

ployed impedance mode with modulated centre spring stiffness as a reference. Mode B applied relative position feedback according to equation 4; mode C used velocity feedback after equation 3. All three modes were carefully tuned to allow for similar achievable speeds and accelerations for the vehicle, comparable to a real quad-rotor. The order of the three modes was selected at random. Trials were aborted if they did not complete within 90 seconds. The subjects also filled out a Task Load Index (TLX) questionnaire to evaluate the cognitive work load; however the analysis of the questionnaires will not be discussed in this paper.

5 Experiment results

Figures 5 (averages and standard deviation) and 7 (close-up on settling time) show the results for the positioning trials with twelve subjects (first experiment). The plots show clearly that positioning accuracy is significantly better for the two admittance modes B ("leaky" position feedback) C (velocity feedback) compared to impedance mode A. Not all subjects were able to complete the task in mode A. It is also visible that subjects were able to complete the tasks more quickly (indicated by lines ending earlier). The differences between mode B and C are less pronounced, but position feedback using the leaky integrator shows better positioning accuracy and less outliers. Settling times (the time from getting within 10% of the distance to the target until maintaining three consecutive seconds close to the target) are on average 15.5 seconds for mode B and 17.1 seconds for mode C (standard deviation 11.2 and 11.7), which is comparable.

Figure 6 shows the paths taken by each subject in the three different modes. Again there is a clear difference between impedance feedback and the two admittance modes. Both admittance modes show similar performance, but here velocity feedback (mode C) is slightly smoother and more precise. This is not surprising, as the vehicle is moving at high velocity, and stationary positioning accuracy is not important in this task. Table 4 shows some statistics of the path following task. The statistics confirm that the subjects performed better in the two admittance modes than in the reference impedance mode. Only half the subjects were able to complete the task in mode A. Mode B and C show significantly less collisions with obstacles, and a shorter total distance travelled (the shorter the distance, the more direct the route along the path). Note that only subjects who completed the task are considered - this means that the statistics for mode A are biased, as the subjects that completed the task are expected to be more skilled at the given tasks. Any differences between mode B and C are small and inconclusive, but both modes show significantly better performance than mode A.

An additional experiment was carried out using a real quad-rotor, however due to the lack of accurate velocity sensing it was not possible to recreate the full system. As a preliminary test, the quad-rotor (Ascending Technologies Hummingbird) was equipped with a downward-looking IR dis-

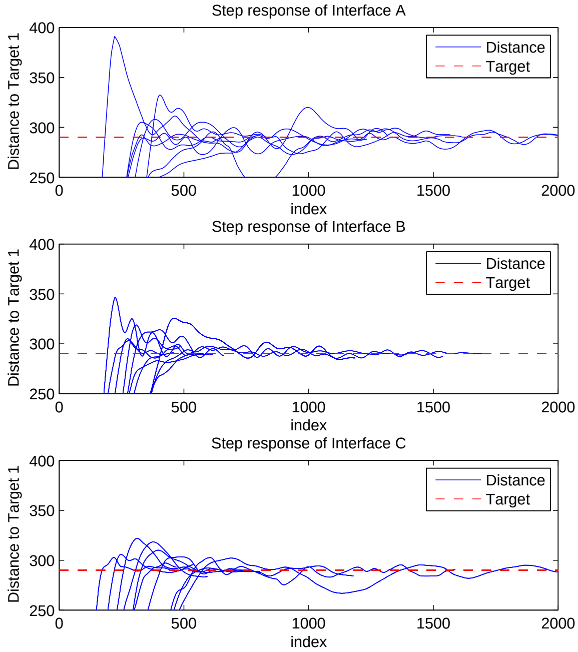

Figure 7: Detail of settling time for Mode A, B and C (top to bottom).

tance sensor to measure altitude above ground. The altitude (measured at 10 Hz) was fed into the vehicle observer running within the haptics subsystem at 1000 Hz. The user-applied force F_u was used as the control input of the vehicle, and also as the feed-forward term for the vehicle observer (i.e. the vehicle dynamics simulation as in the simulator). As only altitude data was available the vehicle dynamics were only run in 1D, mapping the actual altitude above ground to the joystick. By tuning the relative gains between feed-forward and sensor feed-back it was possible to minimise the perceived time lag, despite the very slow altitude sensor. Lateral control of the vehicle was done using F_u, however there was no feedback to the joystick, and lateral displacement was set to zero. Accurate altitude control of the vehicle was possible, and the altitude feedback allowed for controlled landings, or ground avoidance by holding the joystick at a fixed level. Figure 8 shows the response of the joystick to the vehicle liftoff. Due to the limitations of the system no controlled trials were carried out with this setup, and this is left for future work.

6 Limitations and Future Work

A number of assumptions were made with regard to the simplified vehicle dynamics. Preliminary experiments with 1D-feedback of altitude are promising, and suggest that it is possible to achieve sufficiently good tracking of the actual system state while using a very simple "point-mass" model. Extending the current implementation to three dimensions is still on-

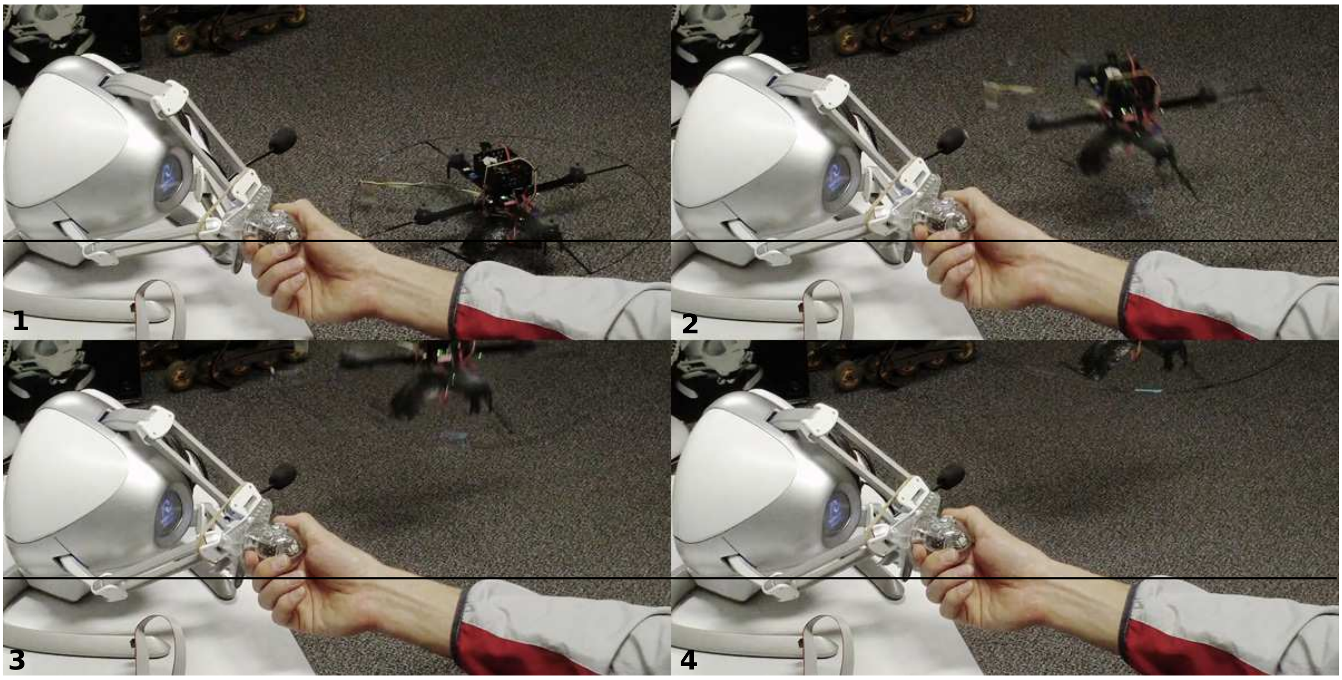

Figure 8: Image sequence of quad-rotor takeoff with 1D admittance-mode haptic feedback. Altitude feedback is derived from a downward looking IR range sensor, coupled to the 1000 Hz vehicle observer that drives the haptic system. The black line illustrates the stick position at zero altitude.

going work. The emulation of admittance mode on the low-cost Falcon device, which was designed as an impedance device, has its limitations. Achievable rigidity is relatively low, and was additionally limited by the low resolution of the encoders, and resulting lack of achievable damping. Despite the limitations the joystick provides a reasonable feedback of the vehicle motion and inertia, and allows for sufficiently accurate control. The feedback of the vehicle stopping in front of a wall however is less distinct and could be stronger. Similarly the large forces expected during high acceleration are not transmitted due to the limited rigidity of the joystick, which makes control somewhat less direct during rapid movements. A joystick with more available force, or an actual admittance device with high rigidity would most likely improve this. This work also relies on the availability of velocity measurements. It is plausible that sufficiently good measurements can be achieved with onboard sensors, although not necessarily under the payload constraints of the Hummingbird quadrotor. Possible sensors are range sensors (laser, ultrasonic or radar), vision sensors (optical flow, stereo), inertial sensors (integration of filtered acceleration), external tracking systems, GPS, or a combination of the above. Future work is to implement the proposed system in 3D using a real quadrotor vehicle and a subset of the suggested sensors to show the feasibility of this approach under more realistic conditions. Issues that need to be addressed are the influence of roll and pitch motions on sensor data, tracking performance of the vehicle observer under realistic conditions, and calibration of the system to match the observer to the actual vehicle dynamics.

7 Conclusion

This paper discusses a new approach for haptic teleoperation of hovering vehicles with unlimited workspace. We propose an admittance-mode haptic framework, and give a solution to address the problem of how to map an unlimited workspace of the robot to a limited workspace of the joystick. With the proposed framework it is possible to provide 1:1 position feedback to the pilot during low-speed manoeuvers, and gradually shifting towards velocity feedback when travelling larger distances. Any additional obstacle avoidance or guidance schemes can easily and transparently be integrated and will automatically map to the haptic system. By using an observer running at high frequencies for estimating the vehicle state, it is possible to achieve fast, smooth and stable haptics response, while incorporating slower sensor measurements to ensure that the observer tracks the state of the vehicle. Data from experiments with 13 subjects was presented and illustrates the overall feasibility of the concept. Two different admittance mode schemes were tested, velocity feedback and (leaky) position feedback. User performance was found to be equally good in both modes. The “feel” of the two modes is quite different, and it may depend on the application which mode should be given preference. The current results are sufficiently promising to pursue this approach for teleoperation of a real flying vehicle.

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