Representation of Vehicle Dynamics in Haptic Teleoperation of Aerial Robots

Xiaolei Hou, Robert Mahony, Felix Schill

***Abstract*— This paper considers the question providing effective feedback of vehicle dynamic forces to a pilot in haptic teleoperation of aerial robots. We claim that the usual state-of-the-art haptic interface, based on research motivated by robotic manipulator slaves and virtual haptic environments, does a poor job of reflecting dynamic forces of a mobile robotic vehicle to the user. This leads us to propose a novel new force feedback user interface for mobile robotic vehicles with dynamics. An analysis of the closed-loop force-displacement transfer functions experienced by the master joystick for the classical and the new approach clearly indicate the advantages of proposed formulation. Both the classical and the proposed approach have been implemented in the teleoperation of a quadrotor vehicle and we present quantitative and cognitive performance data from a user study that corroborates the expected performance advantages.**

I. INTRODUCTION

Force feedback or haptic teleoperation of remote robotic devices is a classical topic in robotics. The benefit of haptic feedback in teleoperation applications that require precision and skill of the user is well established [18], [4], [14], [9]. The utility of forcefeedback in teleoperation of mobile vehicles is less well studied. Obstacle avoidance and trajectory guidance control algorithms have been studied for terrestrial wheeled vehicles [5], [6] with force feedback generated by artificial force fields, typically virtual potentials or spring-damper models associated with environmental interaction, that provides the user with a haptic sense of the local environment. In 2002 Lee *et al* [13] provided a user study that indicated that haptic feedback made a significant difference in the performance of a user in navigating through a complex obstacle strewn environment. The problem of force feedback teleoperation of a helicopter has been studied in the Faculty of Aerospace Engineering at Delft University of Technology over the last six years [2], [10], [12], [11]. This work has showed that a simple virtual potential or spring damper system does not provide good haptic cues to the pilot for obstacle avoidance. Instead they use ideas based on the *generalized potential field* [8] that compares estimates of time-to-contact and maximum stopping time to produce a force that becomes noticeable only when the vehicle is performing a manoeuvre that may lead it to come close to collision. Recent work by Brandt [3] also finds a similar time-to-contact cue to be the key to providing good haptic feedback to the pilot. Work by the Mahony [15], [20] has used optic flow as a direct cue for teleoperation of terrestrial wheeled vehicles and for aerial vehicles. The spherical divergence of an optical flow field for a moving vehicle is closely related to time-to-contact and the behavior of the system is qualitatively the same as that obtained in [2], [10], [3], [12], [11] with the added advantage that it is derived from a vision system, one of the lightest, most robust, exteroceptive sensor systems available for a aerial robot. Although there are a range of works concerning haptic rendering of exogenous forces to aid obstacle avoidance and task performance for aerial robotic vehicles the authors are aware of no work based on rendering the inertial forces of the vehicle.

In this paper, we propose a novel haptic control scheme that offers better representation of the dynamic force of mobile robotic vehicles in haptic teleoperation with a particular focus on aerial vehicles. The proposed approach is achieved by configuring the haptic joystick to servo control its position reference based on the velocity feedback from slave robot and measure force applied by user as the control reference input to the robot. This approach should be compared to the classical approach in which the position of the master joystick is used as input to the robot and the force applied to the joystick is derived from data received from the slave vehicle. The velocity of the vehicle is estimated by velocity observer using absolute position and attitude measurement from VICON visual tracking system to regulate the position set point of the joystick, providing the pilot with a feel for the motion of the vehicle, and to provides velocity controller with velocity feedback. The force applied to the joystick is measured and used as the velocity set point for the velocity controller of the aerial robot. In this way the pilot ‘feels’ the force applied to and the motion of the vehicle in a natural manner. Initial analysis indicates that the resulting controllability of the vehicle is significantly enhanced, and pilots have a much better perception of vehicle’s motion and dynamics. A full factorial user study was carried out on a robotic experimental platform to verify that the proposed haptic interface performs significantly better than the state-of-art approach in both quantitative and cognitive measures.

The remainder part of this paper is organized as follows. Section II describes the problem formulation along with a comparison of the state-of-art approach for haptic teleoperation of mobile robots to the new proposed interface with an analysis of user perception of motion for each case. The approach we proposed to represent the vehicle’s dynamics and comparisons upon user perception of two approaches are given in III. The results from the full factorial user

Xiaolei Hou and Robert Mahony are with Research School of Engineering, Australian National University, Canberra, ACT 0200, Australia `xiaolei.hou, robert.mahony@anu.edu.au`

Felix Schill is with Laboratory of Intelligent systems, EPFL, Lausanne CH-1015, Switzerland. `felix.schill@epfl.ch`

study carried out on the robotic experimental platform are presented in Section IV. A short summary is provided in Section V.

II. PROBLEM FORMULATION

This section reviews the state-of-the-art approaches in teleoperation of mobile robots, and provides an analysis of user perception of vehicle dynamic forces.

A. State of the art haptic control

In teleoperation of mobile robots, especially under actuated highly dynamic vehicles such as quadrotors, the mobile robots' dynamics are typically modeled by a simplified second order system

$$\begin{aligned} \dot{x} &= v \\ m\dot{v} &= f \end{aligned} \tag{1}$$

where x is the position of the vehicle, v is the velocity and f is the force applied to vehicle. The quadrotor attitude dynamics are separately controlled using a high gain attitude control loop [19], [16]. However, the low damping coefficient and infinite workspace still demands pilots' skill and expertise in control, and therefore variety of haptic teleoperation schemes are developed to assist the human operator to control the robots.

The most common Teleoperation scheme is to map position of the mater joystick to a velocity reference that is the set point for a local controller onboard the vehicle. Haptic feedback to the pilot is provided by setting force feedback on the master joystick. There is no natural (energy based) choice for the master joystick force feedback since the position of the master joystick and the position of the slave vehicle are only coupled through velocity set point control [22]. As a consequence the system engineer has considerable latitude in choosing the force cues that are reflected to the pilot.

There are two basic variations of velocity haptic control approach. For vehicles with nonholonomic kinematics, the different degrees of freedom in the master joystick are assigned to control of separate linear and angular velocities of the vehicle.

$$\begin{aligned} \dot{x}_s &= k_1 \xi_s \\ \dot{\theta}_{ref} &= k_2 \xi_s \end{aligned} \tag{2}$$

where ξ is the position of the master joystick.

The most common assignment is forward backward motion of the joystick controlling linear velocity while sideways motion of the joystick is mapped to steering control, or angular velocity set point, of the vehicle. Force feedback to the pilot is typically either environmental force[13] or the haptic boundary[1].

The second approach considers systems without nonholonomic constraints such as aerial robotic vehicles. In this case the master joystick position is mapped directly to the 3D velocity set point for the slave controller.

$$\begin{aligned} \dot{x}_{ref} &= k_1 \xi \\ f &= k_2(\dot{x} - \dot{x}_{ref}); \end{aligned} \tag{3}$$

The force feedback in this case can be ...[discuss the various papers here]

B. Analysis of user perception of motion

In this section, we analyze the 'feel' of the most common framework used in the literature, the force feedback architecture in Eqn.3 [21], [7], [17]. The system architecture considered is shown in Fig.1. Note that we are focused on the free space dynamic response of the vehicle in this paper and the force reflection $f := k(\dot{x}_{ref} - \dot{x})$ is based on the velocity tracking error as is the usual practice[21], [7], [17].

To analyze the feel of the pilot interface we will consider the linear response of the system at a set point and compute the transfer function from position ξ to the force reflection f. One has that

$$\frac{f(s)}{\xi(s)} = \frac{k_1 k_2 (\dot{x}_{ref}(s) - \dot{x}(s))}{\dot{x}_{ref}(s)} \tag{4}$$

Denote the linear approximation of the vehicle dynamics around a pseudo-equilibrium (constant velocity trajectory) by G(s). Denote the linear response of the control by C(s), then the closed loop system is given by

$$\frac{\dot{x}(s)}{\dot{x}_{ref}(s)} = \frac{G(s)C(s)}{1 + G(s)C(s)} \tag{5}$$

In order that the pilot interface is sensible, the closed loop system response must be stable and is generally assumed to have DC gain 1, that is achieves exact tracking for low frequency response. In addition, due to physical limitations of the system, the closed- loop system will have a natural bandwidth ω_{BW} beyond which the tracking performance will degrade. A straightforward computation shows that the pilot interface transfer function becomes

$$\frac{f(s)}{\xi(s)} = k_1 k_2 \frac{1}{1 + G(s)C(s)} \tag{6}$$

Equation 6 indicates that the user perception transfer function is equal to the sensitivity function of the closed loop velocity regulation of the mobile vehicle. Based on the assumption that the closed-loop velocity regulation loop has unit DC-gain and bandwidth ω_{BW}, then the bode plot of the frequency response of the user perception transfer function will have the form shown in Figure 2.

Note that for low frequencies the system response is highly attenuated. This corresponds to the fact that for slow manoeuvres the vehicle tracks the demanded reference accurately and there is little or no force feedback to the pilot. Effectively, the system is operating in pure feed forward teleoperation mode. For high frequencies, above those of the bandwidth of the closed-loop frequency tracking response, the user transfer function response is unit gain. This corresponds to inability of the vehicle to track the input of the pilot, effectively the joystick will feel like a spring to the pilot. The most worrying aspect of this analysis is the low-frequency response of the user transfer function. In the range of frequencies that a pilot will typically be controlling the vehicle, then the force feedback is not active providing

Fig. 1. System structure of force feedback approach

Fig. 2. Sensitivity and complementary sensitivity functions of a close loop PID controller and a 2nd-order system without delay

the pilot with no feedback for the inertial dynamics of the vehicle.

Remark: In practice, many of the existing force feedback teleoperation schemes in the literature [7], [20], [15], [10] have focused obstacle avoidance. For the common user interface design, then at low frequencies the pilot will feel the exogenous haptic forces associated with obstacle avoidance and other haptic cues even though they don't feel the vehicle inertia. As such the common user interface may well be ideal for a range of important applications where vehicle dynamics are not important, or the control scheme is capable of dominating the dynamic response of the vehicle.

III. NOVEL APPROACH FOR REPRESENTATION OF VEHICLE DYNAMICS

In this section, a novel new approach is proposed to enable a human operator to perceive the vehicle dynamic states.

A. Novel approach

The approach is based on idea of servo-control of the joystick to control position of master device while measuring the force applied by the pilot on the joystick and using this signal to set the reference signal for the mobile vehicle. Effectively, we are proposing a reversal of the causality of the master joystick, we will measure force and servo position, while the standard approach is to measure position and servo the force. The force on the joystick must either be measured using a force sensor, or if the master joystick is a typical impedance haptic device, by measuring the force input generated by the servo control system to achieve the desired set point.

We propose to continue to use the local velocity tracking control implemented on the mobile vehicle. Thus, the reference $\dot{x}_{ref}$ for the vehicle velocity is a scaled version of the

Fig. 3. System structure of our approach

joystick force f applied, while the set point for the joystick is a scaled version of the vehicle velocity

$$\begin{aligned} \dot{x}_{ref} &= k_1 f \\ \xi_{ref} &= k_2 \dot{x} \end{aligned} \tag{7}$$

Following the same approach discussed in Section 2, subsection B, we consider the pilot interface transfer function for the prosed approach. IN this case the input is the force f while the output is the master joystick position (see Fig.3). one has

$$\frac{\xi(s)}{f(s)} = \frac{k_1 k_2 \dot{x}(s)}{\dot{x}_{ref}(s)} \tag{8}$$

The system transfer function is given by

$$\frac{\xi(s)}{f(s)} = k_1 k_2 \frac{G(s)C(s)}{1 + G(s)C(s)} \tag{9}$$

where $G(s)$ and $C(s)$ denote the system plant of the slave robot and the corresponding velocity controller respectively.

Equation 9 is in the form of the complementary sensitivity function of the closed-loop velocity tracking system for the mobile vehicle. That is the pilot will "feel" the actual closed-loop system response. For low frequencies we see that the complementary sensitivity has gain $k_1 k_2$, corresponding to the case where the pilot applies a force that is converted into a velocity reference and then feels the displacement of the joystick corresponding to the vehicle velocity. In this sense the pilot has direct feedback of the actual motion of the vehicle in the range of frequencies where they will normally be operating the vehicle. At high frequencies, above the bandwidth response of the closed-loop velocity tracking system, the system response attenuates. This corresponds to the pilot pushing on the joystick without causing it to move, corresponding to the failure of the system to track the demanded input.

We claim that the analysis provided indicates that the proposed framework for haptic force feedback teleoperation of mobile robotic vehicles has the potential to significantly improve the pilots perception of the vehicle motion for dynamic systems. We claim that position is a better feedback cue for the velocity of the vehicle than force. Indeed, we believe that the main reason that the accepted approach works at all is that the master joystick position corresponds to the vehicle velocity in the normal operating conditions, and that the haptic feedback is essentially irrelevant. In the proposed approach this correspondence is fundamental in the formulation and is the key to the intuitive appeal of the approach for pilots.

Note that the it is straightforward to add obstacle avoidance forces to the new approach by applying these forces directly to the vehicle and not to the master interface. In this way the vehicle explicitly avoids obstacles and the pilot feels the obstacle avoidance forces as an inability of the system to track their desired reference.

An added advantage of the proposed approach is that the pilot can set a zero velocity reference trivially by releasing the joystick, and consequently applying zero force. This is not possible in the common approach in the literature as the joystick has to be recentered in the master workspace to set zero input, a process that can be difficult without adding additional centering potentials into the master joystick dynamics. This can be of material advantage if the pilot becomes confused or disoriented; releasing the joystick allows the vehicle to stabilize using its autonomous stability regulation and allow the pilot to recover their sense of the vehicles location and goals.

IV. USER STUDY

In this section we present results from a user study that demonstrates the effectiveness of the proposed control architecture.

A. Robotic experimental platform

The haptic teleoperation system is implemented on a Mikrokopter quadrotor flying robot aided with VICON visual tracking system running at 200Hz. The VICON system provides absolute position and attitude with respect to the reference frame of the VICON workspace. A velocity observer is implemented to estimate the robot's velocity for a velocity controller. All four free degree of freedoms of the quadrotor are fully controlled. Velocity controllers for the three translational axis and a position controller are applied for the yaw angle control.

The master device used is the Novint Falcon 3D joystick. A high gain PID controller is implemented to servo control the position of the master joystick to the reference ξ_{ref}. The Bandwidth of the servo control response is in the order of 20Hz and is almost imperceptible to the pilot. A customized grip is added to the joystick that provides an additional degree of rotation in the z-axis of the device (see Fig.5). This degree of freedom is equipped with an encoder to capture angle set point that is used as the reference for the yaw control of the quadrotor. The yaw axis on the master joystick is not force controlled.

All control commands are sent to a uplink module where they are converted into PPM signal and sent to the robot through the standard radio transmitter. A pilot override is available on the control handset to override the automated control.

The vehicle is equipped with an onboard analogue video camera with a 60 degrees field of view. The video stream is routed through a 5.8Ghz wireless video transmitter that is captured in the video capture card of the base station and displayed for the pilot. The system architecture is shown in Fig.4.

The dimensions of the flying area are 4 meters by 5 meters by 2 meters. There are two internal walls of 1.2 meters in height and 2.4 meters in length, see Fig.6, that provide a cluttered environment in which the pilot must manoeuvre the vehicle. Due to the limited workspace, the maximum velocity of x- and y- axis is 0.5m/s, and there is also a boundary with the maximum and minimum altitude of 1.8 meters and 0.2 meter to avoid the robot flying outside the testing area.

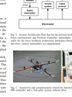

Fig. 4. System Architecture.Note that for the position feedback architecture Force measurement and Position Controller submodules are implemented while for the force feedback architecture alternative Position measurement and force control submodules are implemented.

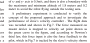

Fig. 5. Sensitivity and complementary sensitivity functions of a close loop PID controller and a 2nd-order system without delay

A preliminary experiment is conducted to verify the concept of the proposed approach and to investigate the performance of slave's velocity controller . The flight data was recorded and shown in Fig.7. The force measured on master device is mapped to velocity set point shown as the green curve in the figure, and according to Newton's third law, this force input is also the force feedback to the pilot, which in Fig.7 is tracked by the slave's velocity shown

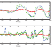

Fig. 6. environment

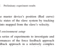

Fig. 7. Preliminary experiment results

in blue curve. The master device's position (Red curve) reflects the dynamic states of the slave system by tracking the position set points mapped from the slave's velocity.

B. Experiment and environment setup

We carried out a series of experiments to investigate and compare the performances of the force feedback approach and the force feedback approach in a relatively complex environment to conduct assigned tasks. A total of six subjects participated in the user study a the full factorial experiment design was performed to eliminate any bias in the results. None of the subjects have prior experiences in piloting remote controlled aeroplanes. There is no trial session available for subjects to learn different control schemes.

Firstly, a positioning task was considered where the goal was to move the vehicle between two stationary set points and then stabilize the vehicle at the new position as quickly as possible. Three transitions of the vehicle were required of each subject for each of the control schemes. The second task was a path following task where goal was to manoeuvre the vehicle around a predefined path through a cluttered 3D environment as quickly and effectively as possible, without colliding with the environment. A single transit of the path was undertaken for each subject.

Since our proposed approach aims to better represent the dynamic force of the vehicle instead of the environmental force, there is no environmental force algorithm implemented for this user study so that pilots are fully responsible for the robot's safety during the user study.

C. Experimental results

The flight data was logged for quantitative analysis and the NASA Task Load Index (TLX) questionnaire was completed by each subject after each scheme to obtain a qualitative measure of user perception of the system response. For the positioning target task, we use the step response of the transition between targets to provide rise time, settling time and overshoot metrics for the user performance from the quantitative data logged. It is more difficult to determine effective metrics for the path following task and we have used total time and average velocity of the flight although it is clear that these two metrics will be somewhat confounded in the statistical analysis.

The cognitive load data and flight data of positioning target and path following are shown in Table.II, I and III as well as the two samples T-test results with heterogeneous variances. For the rise time, settling time, total time data and task load index, the lower the value is, the better the approach performs; while the high average velocity means fast and smooth flight that implies a better approach used for the flight. The mean and standard deviation of the flight data and task load index are shown in Fig.8.

The Null hypothesis H_0 is $\mu_1 = \mu_2$ and therefore H_1 is $\mu_1 \neq \mu_2$, $\alpha = 0.2$. For the positioning target task, both t values of the rise time and settling time t are greater than $t_{0.2}(6)$ ($t_{0.2} = 1.4398$). We claim that with 80% confident level, we can reject the hypothesis H_0. For the path following task, both t values of the flight time and average velocity t are smaller than $t_{0.2}(6)$. So we claim that with 80% confident level, we can accept the hypothesis H_0. Finally, the task load index t test shows a diverse result from the flight data. With 80% confident level, we can reject the hypothesis H_0 for path following task but accept the hypothesisH_0 for positioning target task.

From the T-test results provided above, with only 6 subjects, we can still observe some improvements in rise time and settling time of transitions between targets in flight data and better cognitive load performance in task load index data. On the contrary, no statistical significant improvements can be found in quantitative data, by contrast, we can see the significance in statistical for the flight data of path following and the TLX data of positioning target task.

V. CONCLUSIONS

The position feedback approach for haptic teleoperation of aerial robotic vehicle to better represent vehicle's dynamic

TABLE I

STATISTICAL RESULTS OF POSITIONING TARGET

Task	Scheme	mean	standard deviation	T value
Rise time	A B	15.18 11.47	1.81 1.38	4.01
Settling time	A B	46.47 36.99	8.02 9.29	1.89

TABLE II

STATISTICAL RESULTS OF PATH FOLLOWING

Task	Scheme	mean	standard deviation	T value
Total flight time	A B	88.11 89.36	9.08 10.66	0.22
Average velocity	A B	0.317 0.356	0.034 0.051	1.54

force is proposed and implemented on a robotic platform. A small scale user study was carried out to investigate the performance of the proposed approach with comparisons to the most used haptic control approach. According to the figures and data above, with a small sample, the statistical significance can be obtained in either quantitative or cognitive analysis for two tasks, which demonstrates that the proposed approach has a better performance for piloting the robot to perform different tasks. It is interesting to find that, even though pilots do not feel much different in positioning target task, the quantitative data shows significant improvement in performance, which implies that in the situation when the pilots want to quickly change the velocity of robot, two approaches are felt similar to user, however, the proposed approach can change the robot's velocity quicker than the force feedback approach; and in the path following task, robot travels smoothly through the environment without varying the velocity frequently, ant then pilots perceive differently since two approaches reflect quite different information to user, while they perform similarly to each other. The results reveal the benefit for representing dynamic force of slave robot on the master device, which is ability to change the velocity quickly, and providing rich haptic cues to pilot during flight to better represent the states of the vehicle.

VI. ACKNOWLEDGMENTS

This research was supported by the Australian Research Council through Future Fellowship FT0991771 Foundations of Vision Based Control of Robotic Vehicles. The authors would like to thank Alex Martin, Evan Slatyer and Kamran Siddique for help with the experimental platform.

REFERENCES

[1] S. Nahavandi B. Horan, Z. Najdovski and E. Tunstel. 3d virtual haptic cone for intuitive vehicle motion control. In *Proc. of IEEE Symposium on 3D User Interfaces*, pages 67–74, 2008.

[2] H. W. Boschloo, T. M. Lam, M. Mulder, and M. M. van Paassen. Collision avoidance for a remotely-operated helicopter using haptic feedback. In *Proc. IEEE Int Systems, Man and Cybernetics Conf*, volume 1, pages 229–235, 2004.

TABLE III

TLX RESULTS

Task	Scheme	mean	standard deviation	T value
Positioning target	A B	6.08 6.04	0.65 0.73	0.03
Following path	A B	6.08 4.18	0.99 0.39	1.79

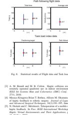

Fig. 8. Statistical results of Flight data and Task load data

[3] A. M. Brandt and M. B. Colton. Haptic collision avoidance for a remotely operated quadrotor uav in indoor environments. In *Proc. IEEE Int Systems Man and Cybernetics (SMC) Conf*, pages 2724–2731, 2010.

[4] Masaya Kitagawa Brian T. Bethea, Allison M. Okamura. Application of haptic feedback to robotic surgery. *Journal of Laparoendoscopic and Advanced Surgical Techniques*, 14(3):191–195, June 2004.

[5] N. Diolaiti and C. Melchiorri. Teleoperation of a mobile robot through haptic feedback. In *Proc. IEEE International Workshop 2002 HAVE Haptic Virtual Environments and Their Applications*, pages 67–72, 17–18 Nov. 2002.

[6] I. Elhajj, N. Xi, Wai Keung Fung, Yun Hui Liu, W. J. Li, T. Kaga, and T. Fukuda. Haptic information in internet-based teleoperation. *IEEE/ASME Transactions on Mechatronics*, 6(3):295–304, 2001.

[7] P.R. Giordano, A. Franchi, C. Secchi, and H.H. Bulthoff. Towards a navigation system for autonomous indoor flying. In *Proceedings of 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 163–170, 2011.

[8] B. H. Krogh. A generalized potential field approach to obstacle avoidance control. In *Proc. International Robotics Research Conference*, 1984.

[9] A. Kron and G. Schmidt. Haptic telepresent control technology applied

to disposal of explosive ordnances: Principles and experimental results. In *Proceedings of IEEE International Conference on Robotics and Automation*, volume 4, pages 1505–1510, 2005.

[10] T. M. Lam, H. W. Boschloo, M. Mulder, and M. M. van Paassen. Artificial force field for haptic feedback in uav teleoperation. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 39(6):1316–1330, 2009.

[11] T. M. Lam, M. Mulder, and M. M. van Paassen. Haptic feedback for uav tele-operation - force offset and spring load modification. In *Proc. IEEE Int. Conf. Systems, Man and Cybernetics SMC '06*, volume 2, pages 1618–1623, 2006.

[12] T.M. Lam, H.W. Boschloo, M. Mulder, M.M. van Paassen, and F.C.T. van der Helm. Effect of haptic feedback in a trajectory following task with an unmanned aerial vehicle. In *Systems, Man and Cybernetics, 2004 IEEE International Conference on*, volume 3, pages 2500–2506, vol.3, 10-13 Oct. 2004.

[13] Sangyoon Lee, G. S. Sukhatme, G. J. Kim, and Chan-Mo Park. Haptic control of a mobile robot: a user study. In *Proc. IEEE/RSJ Int Intelligent Robots and Systems Conf*, volume 3, pages 2867–2874, 2002.

[14] M Moallem M Tavakoli, R V Patel. Haptic interaction in robot-assisted endoscopic surgery: a sensorized end-effector. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 1(2):53–63, January 2005.

[15] Robert Mahony, Felix Schill, Peter Corke, and Yoong-Siang Oh. A new framework for force feedback teleoperation of robotic vehicles based on optical flow. In *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*, 2009.

[16] D. Mellinger, N. Michael, and V Kumar. Trajectory generation and control for precise aggressive maneuvers with quadrotors. In *Proceedings of the 12th International Symposium on Experimental Robotics*, 2010, Delhi, India., Dec 2010.

[17] S. Carloni R. Mersha, A.Y. Stramigioli. Bilateral teleoperation of underactuated unmanned aerial vehicles: The virtual slave concept. In *Proceedings of the 2012 IEEE International Conference on Robotics and Automation, Date of Conference: 14-18 May 2012*, may 2012.

[18] A.M. Okamura. Methods for haptic feedback in teleoperated robot-assisted surgery. *Industrial Robot: An International Journal*, 31(6):499 – 508, 2004.

[19] P. Pounds, R. Mahony, and P. Corke. Modelling and control of a large quadrotor robot. *Control Engineering Practice*, 18(7):691 – 699, 2010. Special Issue on Aerial Robotics.

[20] Felix Schill, Robert Mahony, Peter Corke, and Luke Cole. Virtual force feedback teleoperation of the insectbot using optic flow. In *Proceedings of the Australasian Conference on Robotics and Automation*, Canberra, Australia, December 2008.

[21] Hyoung Il Son, L.L. Chuang, Junsuk Kim, and H.H. Bulthoff. Haptic feedback cues can improve human perceptual awareness in multi-robots teleoperation. In *Proceedings of 11th International Conference on Control, Automation and Systems*, pages 1323–1328, Oct. 2011.

[22] Stefano Stramigioli, Robert Mahony, and Peter Corke. A novel approach to haptic teleoperation of aerial robot vehicles. In *Proceedings of the International Conference on Robotics and Automation*, 2010.