2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

A Novel Approach to Haptic Tele-operation of Aerial Robot Vehicles

Stefano Stramigioli, Robert Mahony, Peter Corke

Abstract— **We present a novel, simple and effective approach for tele-operation of aerial robotic vehicles with haptic feedback. Such feedback provides the remote pilot with an intuitive *feel* of the robot's state and perceived local environment that will ensure simple and safe operation in cluttered 3D environments common in inspection and surveillance tasks. Our approach is based on energetic considerations and uses the concepts of network theory and port-Hamiltonian systems. We provide a general framework for addressing problems such as mapping the limited stroke of a 'master' joystick to the infinite stroke of a 'slave' vehicle, while preserving passivity of the closed-loop system in the face of potential time delays in communications links and limited sensor data.**

I. INTRODUCTION

Over the last decade there has been significant progress in the development of aerial robotic vehicles for inspection and surveillance tasks. Potential applications include, for example, inspection of piping and cabling and other infrastructure in factories and mines, often mounted inaccessibly on walls or ceilings. Bridges, dams, pressure vessels and other large scale civil infrastructure are inspected regularly for signs of damage or weakness. Lift shafts and ventilation ducts also require regular inspection, to mention just a few of the possibilities. Early work used helicopter platforms [1]–[3], however, the large rotor disk of a helicopter is not well suited to inspection tasks in cluttered environments. Other aerial platforms, of which the quadrotor platform [4]–[7] is probably the most popular, have been heavily studied in recent years. A majority of the published work to date has concerned the modelling and design of controllers for autonomous operation of aerial robotic vehicles [8]–[12]. However, most inspection and surveillance tasks cannot easily be automated due to the need for high-level reasoning and specialist and context specific knowledge inherent in the task. Human inspectors are highly trained in the particular infrastructure inspection task considered, however, they will not be trained in piloting aerial vehicles, and moreover, during inspection tasks most of their attention is focused on the sensor data and not on the vehicle. For inspection to be undertaken remotely by an aerial robotic vehicle the inspector must be provided with an intuitive and natural interface for control of the vehicle. Recently several authors have recognised the importance of developing tele-operation control for aerial robotic vehicles [6], [8], [13]–[16]. This topic is still very much in its infancy and, while promising, there has been little effort to apply some of the established tele-operation algorithms developed for traditional manipulator arms [17]–[19] to the particular problem of control of aerial vehicles.

The contribution of this paper is a general framework for the design of haptic tele-operation algorithms for the control of aerial robotic vehicles. The proposed approach is based on a port-Hamiltonian system framework [20]. The master and slave systems are separately controlled by local non-linear control loops that enforce a local port-Hamiltonian behaviour that mimics the response of a suitable mechanical system. The mechanical model used to develop the local control is chosen to provide the pilot with intuitive control of, and feedback to, the vehicle motion and its environment. The parameters of the local mechanical model govern the feel of the system to the pilot and the response of the vehicle. It is these parameters that are transmitted as control signals to update the control action of the master and slave systems. Thus, only the parameters of the local control responses are transmitted across the communication link with its associated lower bandwidth and variable time delays. High bandwidth control response of the systems, both master and slave, are ensured by the local control loops implementing port-Hamiltonian dynamics.

Since the closed-loop master and slave systems mimic mechanical systems we can measure the energy stored or released locally and use this information to define local energy stores for the two systems. These two energy stores are allowed to trade energy back and forward over the communications channel in order to balance the local energy available to either the master or slave. The local control loops are designed in such a way that they must draw energy only from what is available in the local energy buffer. As a consequence, the overall response of each local control system is bounded by the total available energy in the combined system and stability of the tele-operation system can be guaranteed. This approach is however infeasible if the 'slave' aerial vehicle is directly incorporated in the closed-loop system, since any heavier than air vehicle continually expends energy to maintain flight and a faithful model of the vehicle response would quickly consume all the energy available in the finite local energy buffer. To overcome this difficulty we introduce a *virtual* vehicle that simulates the rigid-body-dynamics of the real vehicle, but flying in an environment in which the energy dissipation associated with maintaining steady-state flight is fully compensated. (In this paper we propose a simple translational model of the vehicle dynamics flying in zero gravity environment.) The virtual vehicle is coupled energetically to the master, that is, it trades

S.Stramigioli is with the University of Twente, 7500 AE Enschede, The Netherlands s.stramigioli@utwente.nl

R. Mahony is with the Australian National University, 0200, Australia Robert.Mahony@anu.edu.au

P. Corke is with the Queensland University of Technology, Australia. peter.corke@qut.edu.au

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energy with the master. A second local non-linear control loop is implemented to control the actual dynamics of the aerial vehicle, implementing an analogue of a visco-elastic coupling between virtual and real vehicles. Control of the real vehicle is based on set-points drawn from the state of the virtual vehicle, while the response of the real vehicle due to interaction with the environment, gusts, disturbances, etc, is mapped back to the virtual vehicle as a coupling force. Since these signals are purely internal to the controller it is simple to measure the total energy associated with this interaction and replenish the local store appropriately, either to ensure energy conservation or to implement some level of dissipation. The actual control schemes used in the local loops is secondary to the conceptual framework of the control, however, we provide an example of choices and a simulation of its performance.

The paper is organised as follows: In §II the main conceptual points of the proposed strategy will be discussed in detail. In §III the fundamental concept of the virtual slave will be introduced together with its coupling to the real slave. A simple implementation of the master controller will be introduced in §IV. In §V simulations will show the proper behaviour of the strategy.

II. Background and philosophy

A haptic tele-operation system comprises a master, a slave and a communications link between them. The master is a physical joystick device that is manipulated by the human operator and is capable of force feedback. The aerial robot is the slave, responding to state changes commanded by the master and returning sensory perception that results in feedback to the master. The communications link may be the internet, in which case the transit time for messages is significant with respect to the dynamics of the flying robot as well as being variable.

There are a number of unique challenges in developing a haptic tele-operation control algorithm for an aerial vehicle:

a) Finite stroke joystick: The joystick control has finite configuration space (range of motion) while the robot has an infinite configuration space. As a consequence, it is impossible to directly map motion of the joystick to that of the vehicle as is done in classical bilateral force feedback tele-operation.

b) Pervasive dissipation: A simple energetic coupling between the master and slave vehicle will maintain a total energy between the two systems. However a heavier-than-air vehicle is continually dissipating energy to maintain flight, even if it is stationary, and will quickly exhaust the capacity of the master to provide the necessary energy. In practice, the vehicle needs to draw from an effectively infinite energy well, its battery charge or fuel supply, to provide the energy to maintain flight. It is not a good idea to model such an energy supply explicitly in the coupling between master and slave since the total energy between the two systems would be effectively infinite and there is no guarantee of overall stability of the system. Thus, it is necessary to isolate the energy flow that is being channelled into sustaining flight of the vehicle from the energy that is associated with manoeuvering the vehicle.

c) Lack of measurements: Many of the variables in the state of an aerial vehicle are difficult to measure. This is particularly true of the aerodynamic variables such as total thrust or drag on rotors, angle of thrust, aerodynamic drag on the vehicle airframe, etc. It is also true of rigid-body state of the vehicle, in particular the position and linear velocity of an aerial vehicle can be very difficult to measure accurately and effectively (the attitude conversely can be derived from measurements obtained by an inertial measurement unit (IMU)). Moreover, unlike classical bilateral force-feedback tele-operation of a manipulator there are no direct interaction forces with the environment and force feedback for the operator must be derived from non-contact perception of the environment from the flying robot. In recent work [13], [14] we propose the use of optical flow to indicate proximity to obstacles.

In addition to these challenges the system will suffer the same issues as classical haptic tele-operation schemes: unknown and dynamic environments, unknown and possibly varying time-delays in the communications link and different power scaling between the master and slave. The goal is to guarantee stability and if possible passivity of the system while maximising force transparency or feel for the environment to the user.

A port-Hamiltonian system is a dynamical system that interacts with the environment through dual variables, known as a port, that comprises effort and flow [20]. Potential energy in the system can be stored in, or extracted from, springs or capacitors, while (generalised) kinetic energy is stored in inertias or inductors. For example, the master system or joystick interacts with the pilot through velocity of, and force applied to, the joystick.

We propose to develop a local control for the joystick by measuring velocity and/or force of the joystick and using these as port variables for a Hamiltonian system. The apparent dynamics of the joystick (springs, dampers and inertia) is a function of the local controller and its parameters can be varied in real-time based on signals from the slave. Changes in energy associated with parameter variation, for example changing spring stiffness or set point, requires an adjustment to the local energy buffer. By keeping track of the total energy in the local control loop we ensure passivity of the algorithm. This concept is repeated at the slave, except that the tele-operation system is interfaced to a virtual vehicle rather than the real vehicle. Once again a local controller provides the desired closed-loop mechanical dynamics for the virtual vehicle. The parameters may be changed based on signals from the master. Again, changes in energy associated with parameter variation requires an adjustment to the local energy store.

The master and slave energy stores are connected via an energy balancing law over the communications link. This is done in such a way that no energy increase takes place even in the presence of time varying delays: if energy is transmitted it is immediately subtracted from the local energy and if energy arrives from the other source it is added to the local storage. Use of the energy on either sides of the tele-operation link is modulated by the local control system parameters.

The virtual vehicle operates in a world without friction or gravity and the only disturbances to its motion comes from a *coupling* to the real vehicle dynamics. Since this coupling is implemented by a local controller at the slave side the energy circuit on the virtual vehicle is decoupled from the real vehicle guaranteeing stability, even in the presence of unknown and varying time-delays.

A local control loop must be implemented to provide a visco-elastic coupling between the virtual and the real vehicle. This control design can be based on any of the recent control developments documented in the literature [6], [10], [12], [16]. The key idea here is that the control takes input from the state of the virtual system as set points for a control algorithm without making this an explicit energetic coupling. As such the control can deal with the pervasive dissipation of the lift as well as partial sensor information. Conversely, the sensor suite on the aerial vehicle is used to provide information on the motion of the vehicle relative to the local environment. This information is fed back as an external force on the virtual vehicle. The action of the external force on the virtual vehicle is implemented in a very particular way to ensure that no energy will be injected into the virtual vehicle. Thus, disturbances and the environmental sensory input from the real vehicle is reflected to the virtual vehicle and will eventually be fed back to the pilot over the communications channel via changes in parameters of the local control at the master unit. Note that the coupling between the real and virtual vehicles is done in the vehicle avionics and does not suffer from the time-lags inherent in the communications link.

III. The "*virtual* slave" concept

In this section we present details on the local control design for the 'slave' aerial robotic vehicle. The proposed strategy is to define *virtual* system dynamics for the rigid-body motion of a vehicle, simulated in real-time on the avionics of the real vehicle; this is represented with the left circle in the right box of Fig.1.

This virtual vehicle is the real-time simulation of an idealized vehicle for which all information can be measured and that is moving in zero-gravity space. For simplicity in the present paper we will model the virtual vehicle as point mass dynamics

$$m_v \dot{v}_v = F_v \tag{1}$$

where $v_v \in \mathbb{R}^3$ is the virtual vehicle velocity. The attitude dynamics of the real vehicle will be controlled by the separate, non-passive non-linear control loop on the real vehicle. A more detailed control design may well incorporate attitude dynamics of the virtual vehicle if it were advantageous. We require that the energy associated with motion of the vehicle is drawn from a local energy tank indicated by the corresponding capacitive C element in Fig.1. Let α_v denote

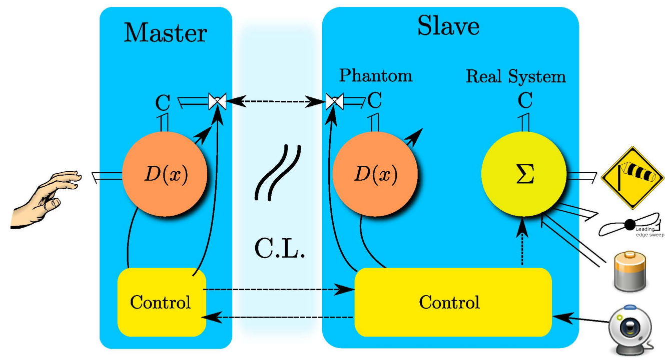


Fig. 1. The main structure of the tele-manipulation chain

the state variable associated with the energy of the local energy store on the slave side of the system associated with the virtual vehicle. The total energy of the virtual slave vehicle is given by a Hamiltonian

$$H(p_v, \alpha_v) = \frac{1}{2m_v} p_v^2 + \frac{1}{2m_v} \alpha_v^2.$$

Let $p_v = m_v v_v$ be the momentum of the virtual slave vehicle, then the Hamiltonian dynamics for the virtual slave, incorporating the local energy store are given by

$$\begin{pmatrix} \dot{p_v} \\ \dot{\alpha}_v \end{pmatrix} = \begin{pmatrix} 0 & \sigma_v \\ -\sigma_v & 0 \end{pmatrix} \begin{pmatrix} \frac{p_v}{m_v} \\ \frac{\alpha_v}{m_v} \end{pmatrix}. \tag{2}$$

This equation is typical of a port-Hamiltonian system with energy function $H(x)$ and skew symmetric interconnection structure J:

$$\dot{x} = J \frac{\partial H}{\partial x}. \tag{3}$$

Due to the skew symmetry of the interconnection matrix J the energy of the Hamiltonian is conserved $\dot{H} = 0$. The initial condition when the vehicle is not moving can be written $(p_v(0), \alpha_v(0)) = (0, m_v \overline{v}_m)$ where $\overline{v}_m$ is the maximum speed allowed for the vehicle.

The variable parameter $\sigma_v := \sigma_v(t)$ is allowed to vary with time and can be modulated as required by the control algorithm. Varying the parameter σ_v acts as a modulated transformer between the local energy buffer and the kinetic energy of the vehicle and does not change the overall energy content. We propose to modulate this parameter based on signals received from both the master and real vehicle, see Fig.1.

In order for the system to behave intuitively, the virtual and real vehicle must influence each other: if due to a command from the master the virtual vehicle accelerates, the real vehicle should do the same and if due to the presence of an obstacle, the vision system of the real vehicle would decelerate the vehicle, this should be mirrored on the virtual vehicle and the effect eventually reflected to the master as well. In order to achieve this, we would like to implement a visco-elastic coupling between the real and virtual vehicle. Such a coupling would have the desired dynamic effect, however, a direct energetic coupling of the real and virtual vehicle may lead to loss of passivity of the tele-operation system and consequent issues with stability.

For the moment we imagine that the full state of the real vehicle can be measured. In this case we can compute the forces generated by any choice of virtual coupling between real and virtual vehicles. Let F_v^c indicate the force that a visco-elastic *coupling* would generate on the *virtual* vehicle. The opposite force would clearly be generated on the real vehicle. Let F_v^m denote the desired force applied to the *virtual* vehicle derived from the signals received from the *master* side of the system. At each instant of time, the combined force applied to the virtual vehicle is

$$F_v = F_v^c + F_v^m.$$

Referring to (2) it is easily verified that this force can be implemented by drawing energy from the local energy store by choosing the modulation parameter as

$$\sigma_v = \frac{m_v}{\alpha_v} F_v. \tag{4}$$

This approach ensures that the visco-elastic coupling implicit in the real-virtual system interaction, and the force imposed by the master, are both implemented in a way that uses only energy from the local buffer. The singularity, occurring when $\alpha_v = 0$, corresponds to the energy tank being depleted as a result of too much local control action. In this case, the desired force cannot be supplied to the vehicle until more energy is provided in the local store. This process lies at the core of the global stability of the system, and is a key aspect of the design approach, however, a mechanism should be implemented in order to prevent the controller entering into numerical singularity. We propose the following simple scheme to deal with this case

$$\sigma_v = \begin{cases} 0 & \alpha_v < \epsilon \ \text{ and } \ F_v v_v > 0 \\ \frac{m_v}{\alpha_v} F_v & \alpha_v \leq 0 \ \text{ or } \ F_v v_v \leq 0 \end{cases} \tag{5}$$

where ϵ is a small positive number to be defined. The second condition in Eq. (5) indicates that if the energy flow is in the direction of the energy tank (for example due to a braking force on the vehicle) we are happy to have energy pumped back into the tank.

In case a sudden excessive motion of the real vehicle would take place as a consequence of for example a gust of wind, this could result in a speed of the real vehicle higher than the define maximum $\overline{v}_v$. In such a situation, the visco-elastic coupling could require a force F_v to the virtual vehicle that cannot be implemented because not enough energy is available (α_v going to 0). The virtual vehicle will not go faster than $\overline{v}_v$. As a consequence of that, the force $-F_v$ applied on the real vehicle would increase slowing down the vehicle and bringing it back to the defined maximum speed and this is a desirable effect.

In practice, the full state of the real vehicle cannot be measured. However, the only input required for implementation of the above control scheme is the definition of the force F_v^c. In practice, we propose to define this force based on sensor input and estimated states. A practical choice is to define the force based on perceived optical flow derived from an onboard camera [13], [14]. The force generated in this manner is naturally dissipative to the motion of the real vehicle and adds robustness to the overall design. Moreover, optical flow has the advantage that it depends inversely on the distance from the environment. Thus, as the real vehicle approaches an obstacle the perceived optical flow increases and the associated damping force that decelerates the vehicle increases. The highly non-linear and complex dependence of this 'pseudo' velocity measure would make direct coupling of the slave local control to the real vehicle impossible. The approach taken, however, neatly separates the complexities of the real vehicle control from the virtual slave response.

As indicated in Fig.1, the real vehicle is influenced by wind, the thrust actuated, vision, control commands and takes its energy from the local battery. A simple model of the real vehicle is

$$m_R \dot{v}_R = -T_R R_R e_z + m_R g e_3 + F_R^d \tag{6}$$

$$\dot{R}_R = R_R (\Omega_R)_\times, \tag{7}$$

$$\mathbf{I}_R \dot{\Omega}_R = -\Omega_R \times \mathbf{I}_R \Omega_R + \Gamma_R + N_R^d, \tag{8}$$

Where m_R is the vehicle mass and $\mathbf{I}_R$ is the rotational tensor of inertia. The state is given by (v_R, R_R, Ω_R) representing linear velocity, attitude expressed as a rotation matrix, and angular velocity in the body-fixed frame. The scalar T_R is the thrust of the vehicle oriented in the body-fixed frame z-axis while g is gravitational constant with acceleration due to gravity oriented in the world frame z-axis. The disturbance force F_R^d and torque N_R^d combine all unmodelled aerodynamic and other effects and Γ_R represents the control torque for the attitude dynamics.

There are many papers written on control of aerial robotic vehicles over the last few years [1], [4]–[10], [16]. It is not the goal of the present paper to provide a detailed development of a control algorithm and we propose a very simple scheme with only partial analysis. Firstly, we assume that there is some form of measure of velocity available. It is sufficient for this to be derived from optical flow and can be non-linear related to the real velocity of the vehicle as long as it has the same direction as the true vehicle velocity. Extracting the directional information of velocity from panoramic optical flow has been recently studied by a number of authors [21], [22] and this information can be reliably extracted in practice. Let ϕ_R denote the estimate of vehicle optical flow, then we have $\phi_R = \nu(t) v$ where v is the true velocity of the vehicle and ν is a time varying positive scaling factor depending on the local environment of the vehicle. We generate a force demand on the vehicle associated with the visco-elastic coupling to the virtual vehicle by

$$F_R^c = k(v_v - \phi_v) = k(v_v - \nu v_R)$$

for a constant gain k. This is a vector force input that is desired to be implemented in (6). We will assume[1] that $|F_R^c| < m_R g/2$ to avoid singularities in the next stage of the design and enforce this requirement by changing the gain k if required. Consider matching the known part of the right hand side of (6) to obtain

$$F_R^c = -T_R R_R e_z + m_R g e_3. \tag{9}$$

As long as $|F_R^c| \neq mg$ this vector equation can be solved for a unique value of T_R and for unique pitch and roll components of the rotation R_R - rotations around e_z are arbitrary. The thrust value can be directly assigned as a set point for the thrust mechanism of the vehicle while the pitch and roll angles are taken as set points, defining a desired attitude R_R^*, for the vehicle, with the yaw chosen to be zero or according to a secondary criteria as required.

To continue we make the assumption that the attitude dynamics are operating on a time-scale that is faster than and distinct from (ie. an order of magnitude faster than) the time scale of the linear dynamics of the real system. This a reasonable assumption in most practical situations and significantly simplifies the development. Although we make this assumption in the present paper the assumption need not be made in general and the following theory can be extended to deal with a full coupling [1], [4]–[10], [16]. With this assumption, however, the attitude dynamics decouple from the linear dynamics of the system. That is we assume that from the point of view of the linear dynamics (9) holds exactly. The linear dynamics become

$$m_R \dot{v}_R = k(v_v - \nu v_R) + F_R^d = k\nu(\frac{v_v}{\nu} - v_R) + F_R^d$$

It is easily verified from this that, for sufficient small disturbances F_R^d and sufficiently large gains k, then $v_R \to v_v/\nu$. The fact that the true vehicle velocity and the virtual are not equal is not an issue in the final performance of the system as it still provides an intuitive response of the slave vehicle from the point of view of the master system.

It remains to show that the attitude dynamics can be stabilised. Equations (7) and (8) are a fully actuated mechanical system for which the state can be estimated based on IMU measurements. It is straightforward to design a passivity based control that stabilises this system around the set point R_R^*

$$\Gamma_R := -k_D \Omega_R - k_P \text{vex}(R_R^\top R_R^* - (R_R^*)^\top R_R)$$

where k_P and k_D are positive gains and vex is the inverse of the $\times$ operator, that is it extracts the unique three vector from a 3×3 skew symmetric matrix that realises the vector product operation. Stability of the control is seen by considering the derivative of Lyapunov function

$$\mathcal{L} = k_P \text{tr}\left(R_R^* R_R^\top\right) + \frac{1}{2}\Omega_R^\top \mathbf{I}_R \Omega_R$$

[1]This assumption implies that the vehicle always applies thrust to overcome gravity. That is, the vehicle never engages in acrobatic manoeuvres such as a loop-the-loop of free fall stall.

One finds that

$$\frac{d}{dt}\mathcal{L} = k_P \text{tr}(\dot{R}_R^* R_R^\top) + \text{tr}((R_R^*)(\Omega_R)_\times^\top R_R^\top) + \Omega_R^\top \Gamma_R + \Omega_R^\top N_R^d$$

Ignoring the disturbance term $\Omega_R^\top N_R^d$ and assuming $\dot{R}_R^*$ is slow with respect to the attitude dynamics (the time scale separation between linear and attitude dynamics discussed earlier) and can be ignored, one obtains

$$\begin{aligned}\frac{d}{dt}\mathcal{L} &\approx k_P \text{tr}((\Omega_R)_\times^\top R_R^\top R_R^*) + \Omega_R^\top \Gamma_R \\ &= \frac{k_P}{2}\text{tr}((\Omega_R)_\times^\top (R_R^\top R_R^* - (R_R^*)^\top R_R)) + \Omega_R^\top \Gamma_R \\ &= \Omega_R^\top \left(k_P \text{vex}(R_R^\top R_R^* - (R_R^*)^\top R_R) + \Gamma_R\right).\end{aligned}$$

Substituting the proposed control yields

$$\frac{d}{dt}\mathcal{L} = -k_D |\Omega_R|^2.$$

Applying an invariant set argument it is straightforward to show that $R_R \to R_R^*$ and $\Omega_R \to 0$.

IV. The Master System

In this paper we consider a single master joystick characterised by a finite stroke $x_m \in [\underline{x}_m, \overline{x}_m]$ and a finite force $F_m \in [\underline{F}_m, \overline{F}_m]$. In steady state it seems plausible that a constant speed of the vehicle would correspond to a constant value on the master side of either a force or a position. The best choice has to do with the haptic feedback that we would like to receive from the slave. Due to either the local vision loop or a gust of wind, the slave could slow down and we would like to reflect this decrease in speed to the master. If we consider an impedance controlled master with finite stiffness as most of the desktop haptic interfaces, it is not possible to impose a position since a strong action of a human operator could easily counteract that, but we can rather control a force F_m within the physical boundary of the device

$$F_m = k(x_m^* - x_m) \tag{10}$$

with

$$x_m^* = v_v \frac{\overline{F}_m}{\overline{v}_v} \qquad k = \frac{\overline{F}_m}{\overline{F}_m - \underline{F}_m} \tag{11}$$

This corresponds to an elastic element k that couples the joystick at configuration x_m to a configuration x_m^* that corresponds to a scaled velocity of the virtual vehicle.

Respectively, on the slave side we may choose the following proportional gain b that will have units of a viscous damper:

$$F_v^m = b(v_v^* - v_v) \tag{12}$$

with

$$v_v^* = x_m \frac{\overline{v}_v}{\overline{F}_m} \tag{13}$$

corresponding to the desired velocity of the master v_v^* that the user wishes to have by keeping the joystick in a position x_m. It is remarkable that such a simple control strategy results in a passive behaviour as shown in the simulation hereafter.

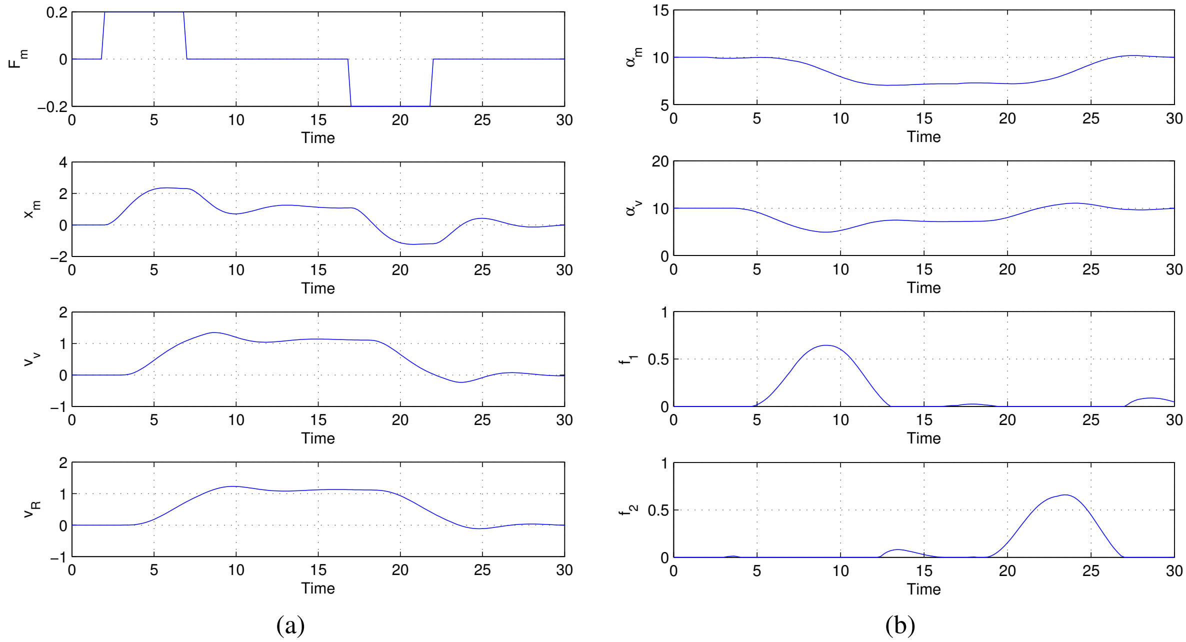


Fig. 2. Behaviour with 1s time delay. User pushes the joystick forward at $t = 2$, and backward at $t = 17$.

V. Simulations

In order to validate the presented algorithm, extensive simulations have been performed using Simulink and the energy based simulation package 20sim. The results shown in Figure 2 are for a transmission delay of $1\,\mathrm{s}$ in both directions, joystick mass of $0.1\,\mathrm{kg}$, slave and UAV mass of $5\,\mathrm{kg}$, joystick spring stiffness $1\,\mathrm{N/m}$ and damping $1\,\mathrm{Ns/m}$, viscous coupling $k = 4$, and input coupling $b = 1$. The master and slave sides are each initialised with $10\,\mathrm{J}$ of energy.

Initially, the vehicle is not moving and the joystick is in the zero position. Figure 2(a) shows that at time $t = 2$ the user applies a force to the joystick, top trace, which the local controller opposes to create the *feel* of a spring/damper system. The joystick begins to move, second trace, and reaches equilibrium around $t = 5$. The joystick position is transmitted to the slave system, via the delay, which causes the slave UAV, third trace, to exhibit discernible motion just before $t = 4$ and the real UAV, fourth trace, starts moving just after $t = 4$, “pulled along” by the viscous coupling.

Figure 2(b) shows the energy levels at each end of the tele-operation system, and the flow between them. The joystick has a small mass so little energy is expended, top trace, to change its momentum. The energy of the slave UAV side, second trace, depletes as the higher-mass slave accelerates. Eventually, around $t = 5$, the master side estimates that it has more energy than the slave side and exports energy to the slave, third trace.

At $t = 17$ the process is reversed. The user applies a backward force on the joystick, which moves in response governed by the local controller. The speed of the slave and UAV return to zero and the energy level on the slave side increases as the mechanical momentum is returned to the energy store. The excess energy on the slave side is eventually returned to the master side, fourth trace.

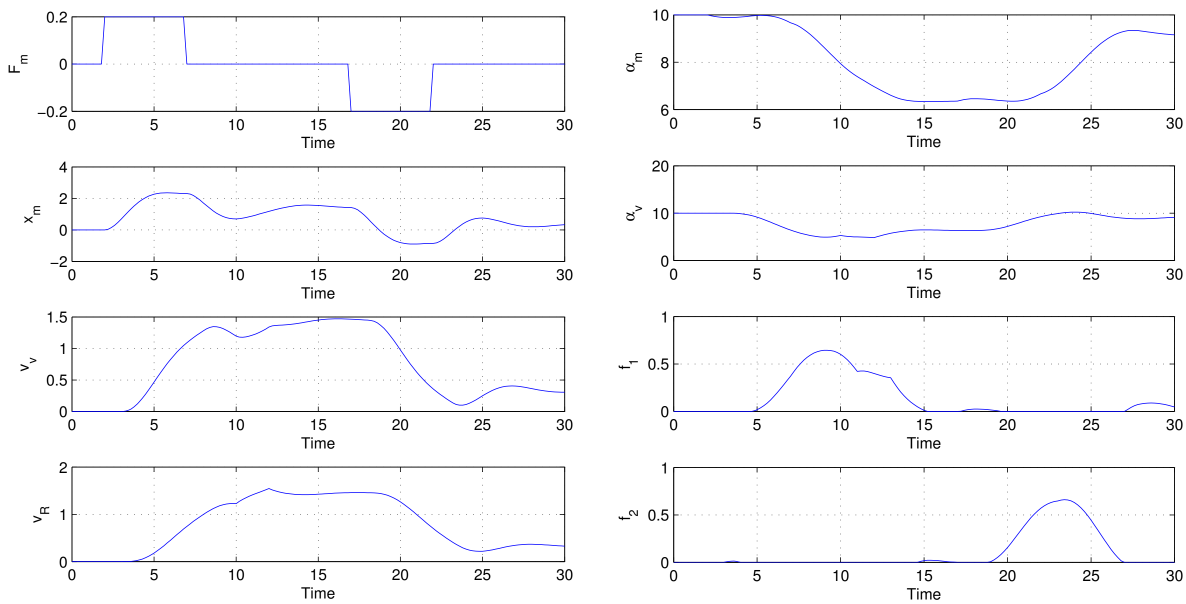
Figure 3 shows the same scenario except that a wind gust, a rectangular pulse at $t = 10$, accelerates the real vehicle. The real vehicle velocity is higher as a consequence of the gust, and the viscous coupling increases the speed of the virtual vehicle but at the cost of extra expenditure of local energy. The extra speed in turn changes the neutral position of the spring on the joystick resulting in a greater joystick displacement, reflecting the greater speed of the real vehicle. The master exports additional energy to the slave in this case, between $t = 10$–15 to compensate for the additional energy expenditure. At the end of this simulation the real and slave vehicles have finite velocity and the joystick has a finite displacement — additional user force is required to push the joystick to neutral to counter the earlier wind gust.

VI. Conclusions

This paper proposes a general scheme for handling the tele-manipulation of flying vehicles. The scheme explicitly handles energy flow and energy balances and can enforce passivity. The approach is general and can be used as the basis of different algorithms. A simple example was considered where a linear elastic control was implemented on the master. Even in the presence of significant time delays of $1s$ the simulations show the system performs well. The limitation of the energy available for moving the virtual vehicle is the key feature that ensures a passive behaviour even in the presence of time delays.

VII. ACKNOWLEDGMENTS

This research was partly supported by the Australian Research Council through discovery grant DP0880509, “Image-based tele-operation of semi-autonomous robotic vehicles”



(a) (b)

Fig. 3. As for Figure 2, but with a wind pulse on the real vehicle at $t = 10$.

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