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A port-Hamiltonian framework for operator force assisting systems: Application to the design of helicopter flight controls

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ABSTRACT

An energetic representation of helicopter flight controls, viewed as an Operator Assisting System, is proposed within the Port-Hamiltonian framework. The assisting controller modifies the dynamical behavior between the pilot stick and the swashplate, linked through a Continuous Variable Transmission, by enforcing force scaling and providing appropriate force feedback to the operator. Generic sufficient conditions are given on the assistance location and structure which allow the assisted system to be dissipative, hence providing nice stability and power scaling properties. Results are applied to the design of an assistance for a simplified flight control system. Simulations show the relevance of the method and are compared to real-life results.

1. Introduction

Helicopter flight controls help the pilot to modify the motion of the rotor blades which will in turn move the aircraft. The cyclic control changes the pitch of the blades cyclically, steering the angle of attack and the lift generated by each blade, tilting the rotor into a particular direction. A swashplate allows to turn the displacements resulting from the flight controls into a rotating motion of the blades, which will be detailed further [21,27]. The main goal of flight controls is to give an assistance to the pilot, which moves a stick, by providing extra power to actuate the swashplate [19,17,25]. In almost all current helicopters, this is achieved through a mechanical Continuous Variable Transmission (CVT) and hydraulic assisting devices, and there is no fly-by-wire, that is no teleoperation. Real helicopter flight controls are far more complicated than power scaling devices, because additional sub-elements allow to achieve different specifications (e.g. trim control, vibration control, automatic pilot control...); however, these elements often interact and their tuning is not simple [9].

Nevertheless, the main question which is addressed in this paper remains to design a power assistance which will be able to actuate the swashplate and generate an appropriate force feedback for the pilot. While the classical approach focuses on shaping the impedance, either of the operator or the load [11,16,29], it seems consistent to study the power flows within the CVT [14], using energetic representations of multiphysics systems such as Bond Graphs [22,18]. These systems interact with external force or flow sources through terminals called ports. Li and Ngwompo [18] showed that power amplification could result from a scaling between the forces (resp. flow) of the operator and environment, which they called Power Transformer (PTF), or a scaling between the flow of one port and the force of another, named Power Gyrator (PGY). As a companion model, a Port-Hamiltonian system is a passive power-based state-space representation that can be derived from a Bond-Graph [7]. Passivity is an important property, as passive Port-Hamiltonian systems enjoy equilibrium stability and asymptotic stabilization by negative output feedback. Further, control laws can be generically derived from this representation by assigning the desired total or potential energies of the closed-loop system [7,4,20,30], e.g. changing this energy to shift the equilibrium to a new one.

The pilot assistance scheme belongs to a class of Operator Assisting Systems (OAS) which consists of devices that help a human user to control and interact with his environment (a "load") through a CVT [14]. The assistance allows the operator to scale his power up, therefore modifying the dynamics between the operator and its environment. These systems find applications in various domains, such as power steering, electric tools, medicine (assisted surgery, prostheses), etc. [6,29].

In this paper, it will be shown that such an Operator Assisting System (OAS) can be considered as a unique Port-Hamiltonian system (the CVT) with several ports, including an operator port (the pilot), a load port (the swashplate) and external ports through

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which an assistance can be applied [14]. The main contribution will be to find the application points and structure of this assistance so that the scaled system (operator-swashplate) is passive. Hence, through this framework, the assistance control design can be handled in a systematic and generic fashion.

Teleoperation shares the notion of “assistance” with OAS, but its frame is fairly different. Teleoperation is a remote control of the flow and effort from one subsystem (the slave) with respect to the behavior of another system (the master), linked through communication buses (e.g. [23,8,28,12]). However, for OAS, the assistance can be considered as one out of the three ports of a unique physical system (the CVT), that modifies the relation between the flows and efforts from the two other external ports, that is the operator and the load. Classical closed-loop control aims at steering an output towards a reference trajectory, and generates an autonomous system. This is not the case for assistive control, which goal consists of enforcing new dynamics between uncontrolled inputs and outputs (forces and flows attached to the operator and environment). This paper shows also how to adapt energetic methods to the specific case of Operator Assisting Systems. Hence, it will be shown that the 3 (or more)-port system has to be transformed into a closed-loop two-port system.

First, current flight controls will be described and the main assistance specifications will be discussed. Then, it will be shown that the flight controls can be represented by a Port-Hamiltonian system with at least three ports. The paper will then explore the conditions under which the assistance generates a dissipative force-scaling system. The results will be applied to the specific case of helicopter flight controls; simulations of the simplified system under assistance will be compared to a simulated multibody model, close to the actual system, and to experimental results, showing the relevance of the control design.

2. Energetic representations and dissipative-based control of operator assisting systems

2.1. Three-port linear representation and control objectives

In this paper, only the restricted class of OAS following Definition 1 will be considered:

Definition 1 *([14]).* An Operator Assisting System is a physical CVT manipulator with an assistance that enforces specified dynamical interactions between a unique operator and a unique load (environment).

The definition assumes that only physically continuous systems will be considered for which the assistance is located at least at one port (interface where power is exchanged). From the mathematical point of view, when the dynamics is linear and there is just one point of application of the assistance, the Operator Assisting System can be considered as a three-port model, which is an extension of the two-port model often used for teleoperation (see [23] for a review). This representation allows to characterize the energetic interaction between the operator, load and assistance in terms of inputs and outputs, namely efforts and velocities, measurable at three sets of terminals or ports. Of these six variables, three can be found as “dependent” (outputs), and the remaining ones as “independent” (inputs), which results from the causal analysis of the system (cf. Fig. 1). For the case where the load effort and operator velocities are the independent variables, one obtains:

$$\begin{bmatrix} f(s) \\ v(s) \\ b(s) \end{bmatrix} = \begin{pmatrix} h_{11}(s) & h_{12}(s) & h_{13}(s) \\ h_{21}(s) & h_{22}(s) & h_{23}(s) \\ h_{31}(s) & h_{32}(s) & h_{33}(s) \end{pmatrix} \begin{bmatrix} u(s) \\ e(s) \\ a(s) \end{bmatrix} \tag{1}$$

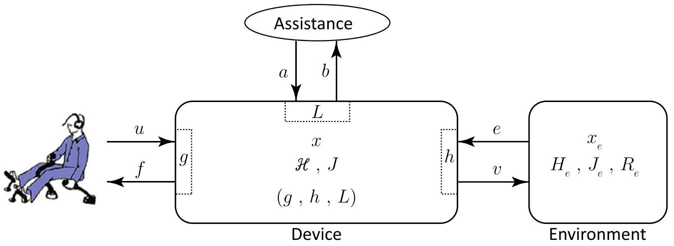

Fig. 1. A representation of Port-Hamiltonian systems under assistance and environment.

where u, f, v, e are respectively the operator velocity and effort, load velocity and effort, a is the velocity/effort of the assistance and b is the dual variable (velocity or effort), s is the Laplace variable. a represents the assistance actuation, and b the reaction of the system on the actuator; product $a.b$ is related to assisting power and is a good indicator for actuator design. Without assistance, the input-output behavior reduces to the well-known hybrid-parameter matrix (or H-matrix, see [23]). There are other configurations depending whether the inputs and outputs are flows and/or efforts. For example, if the inputs are the velocities, and outputs are forces, the matrix giving the relations between inputs and outputs will be called an impedance matrix (e.g. see [23]). While the H-matrix is a standard representation in teleoperation systems, these consider a master robot directly driven by the operator, and a slave robot located in remote environment, which will follow any trajectory ordered by the master through a virtual interface. In the OAS case, the assistance can be considered as an external source acting directly on the manipulator, and thus adds an extra port to this system.

The aim of the assistance is to modify the system of equation (1) to meet the desired closed loop behavior represented by the two-port matrix $\mathbf{H_d}(\mathbf{s}) = (h_d\{ij\}(s))$ in equation (2). The expression of b is not given, as the goal of the assistance is not to shape the relation a, b.

$$\begin{bmatrix} f(s) \\ v(s) \end{bmatrix} = \begin{pmatrix} h_{11_d}(s) & \gamma_E h_{12_d}(s) \\ \gamma_F h_{21_d}(s) & h_{22_d}(s) \end{pmatrix} \begin{bmatrix} u(s) \\ e(s) \end{bmatrix} \tag{2}$$

γ_F, γ_E are flow and effort scaling factors. Matrix $\mathbf{H_d}$ can be interpreted easily physically, as h_{11_d} is the specified unconstrained movement normalized impedance, h_{21_d} is the transfer function of scaled velocity tracking, h_{12_d} is related to force scaling, and h_{22_d} can be called normalized contact admittance [8]. In our case example, the inputs are the swashplate torque and the pilot stick velocity, the outputs are the stick feedback effort and the swashplate pitch velocity. Extra power is needed to move the swashplate and force feedback should be brought to the pilot.

It is possible, for the closed-loop assisted system, to use the terminology of teleoperated systems to characterize the dynamics. Considering the case in the present paper, for which inputs are slave effort and master flow, Hannaford [10] has shown that, for perfect scaling, the H-matrix should be (see e.g. [23]):

$$\mathbf{H_d} = \begin{pmatrix} 0 & \gamma_E \\ \gamma_F & 0 \end{pmatrix} \tag{3}$$

where $\gamma_F = 1$ for force scaling. When $\gamma_F = \gamma_E = 1$, the slave system reproduces the behavior of the master system with fidelity, the impedance from the master and the slave side are equal, and the system is called transparent [24]. For OAS, this will never be possible to achieve perfect transparency because of the closed-loop dynamics, which depends both on the assistance control and the CVT dynamics. While designing a closed-loop assisted system (3) from representation (1) seems easy, the latter however has some drawbacks as it shows only the input/output relations and not the