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Design, Realization and Experimental Evaluation of a Haptic Stick for Shared Control Studies

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Abstract: Shared control is becoming widely used in many manual control tasks as a mean for improving performance and safety. Designing an effective shared control system requires extensive testing and knowledge of how operators react to the haptic sensations provided by the control device shared with the support system. Commercial general purpose haptic devices may be unfit to reproduce the operational situation typical of the control task under study, like car driving or airplane flying. Thus specific devices are needed for research on specific task; this market niche exists but is characterized by expensive products. This paper presents the development of a complete low cost haptic stick, of its initial characterization and inner loop and impedance control systems design, and finally proposes an evaluation with two test cases: pilot admittance identification with the classical tasks, and an entire haptic experiment. In particular this latter experiment tries to study what happens when a system failure happens in a pilot support system built using a classical embedded controller, compared to a system built following the haptic shared control paradigm.

Keywords: shared control, haptic aid, force feedback, motor control

1. INTRODUCTION

Operating a vehicle is a difficult task that requires a high level of cognitive resources. Automated systems have been introduced to assist human operators during control tasks, see Wickens et al. (1998). When automated systems take over the biggest part of a control task, operator's role may be reduced to monitoring the automated system, with the risk of a decreased situational awareness, and ability of understanding the system state for intervening in the control loop when needed, see Endsley and Kiris (1995) and Kaber and Endsley (1997). Haptic aids and the shared control paradigm have been put forth as an appropriate solution to these issues, see Abbink et al. (2008, 2012); De Stigter et al. (2007); Goodrich et al. (2011); Olivari et al. (2014). In addition to the use as an operational aid, shared control could also be considered as a support to training, see Maimeri et al. (2016). Unfortunately design of a haptic aid for shared control is not straightforward and much research is still needed in this field, see for example the many different approaches reviewed in Petermeijer et al. (2015), and the complementary techniques named Direct and Indirect Haptic aid, in short DHA and IHA, presented in Alaimo et al. (2010); other interesting reads on this are: Abbink et al. (2008); Mulder (2007). Experimental campaigns with human subjects and haptic devices are the tools used to provide scientific evidence of otherwise only good conjectures. A large variety of, sometimes relatively cheap, commercial haptic devices, mainly designed for general purpose haptic interaction with virtual worlds, exists. These devices are not well suited for shared control studies since they have shapes, handles, and volumes of motion that are typically very different from the control devices found in vehicles. A smaller niche of haptic devices instead is constituted by force-feedback capable control inceptors that resemble and have the same operational functionality of real vehicle input devices, like steering wheels (Profumo et al., 2013), helicopter cyclic (Nieuwenhuizen and Bülthoff, 2014), pedals (Abbink et al., 2008) and airplane sidesticks (Olivari et al., 2015). These types of device are better suited for man in the loop studies where shared control of vehicles, or of machines in general, is considered; unfortunately, due to belonging to a market niche, the price of commercial products like these is usually high. In order to improve the possibility to perform large shared control experimental campaigns, at a lower price, a novel 2 DOFs haptic stick was designed and realized at University of Pisa with accuracy and cost in mind. A cheap commercial off-the-shelf force-feedback enabled joystick, sold for the gaming market, was modified in order to allow the degree of accuracy needed by haptic experiments. This work is part of an ongoing work aiming at realizing a 4 DOFs haptic stick.

The paper is organized as follows: Section 2 presents the modified joystick architecture, the results of open loop identification tests, and a preliminary closed loop validation. Section 3 presents the results of the multi-sine

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identification process applied to the closed loop joystick dynamics. Section 4 presents the results of two different test cases adopted as validation benchmarks.

2. HAPTIC JOYSTICK DESIGN

This section describes the new haptic stick design process. Only a few force feedback joystick exist in the gaming market; the Logitech Wingman Strike Force joystick was selected for its mechanical simplicity and ease of modification. The electro-mechanical part of the original joystick is composed of an actuated 2 DoFs gimbal powered by two identical brushed DC motors with a gearbox transmission built directly inside the gimbal, and by two potentiometers to pick-up the angular position. A slight backlash is present at the stick, mainly due to the plastic gears of the original stick, on both roll and pitch axis. This type of hardware makes electrical modifications very easy. The only original part remaining in the proposed Haptic stick is the stick mechanics, the motors and the potentiometers; all the electronic control boards were replaced with high performance integrated DC motor controllers and a new control electronics.

In order to implement an haptic feedback, the joystick must appear as a virtual mass-spring-damper system (usually with a critically damped transient response), it should be possible to set dynamically the neutral point (the rest point of the spring), and to inject external forces on the stick to implement an haptic cue. Given the simple decoupled mechanics of the proposed joystick, this goal may be achieved by implementing an inner motor current controller (torque, or force at the joystick tip, is linearly proportional to the motor rotor current), and an outer impedance controller that emulates the presence of a spring and a damper of given stiffness and damping factor.

The control architecture of the proposed haptic stick is depicted in Figure 1. The internal current control loop tracks torque references, and the outer impedance control loop implements the desired spring-damper behavior with configurable stiffness and damping factors. The Desired Position input controls the neutral point of the stick, and the Desired Torque input is used to generate the haptic Force on the stick. Both control loops were implemented on a 32 bit microcontroller and run at 2000 Hz. Each

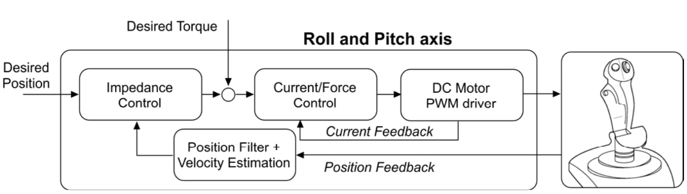

Fig. 1. Haptic stick control system architecture

of the two motors is controlled trough a classical H-bridge implemented by low cost yet accurate and powerful integrated circuit that includes a current sensor. The H-bridge is controlled by two signals, a binary signal indicating the direction of current flow (for positive and negative currents/torques) in the motor windings, and a pulse width modulated signal (in our case at 21 kHz) which, exploiting the natural low pass dynamics of the DC motor, produces an armature voltage proportional to the duty cycle. More details on brushed DC motor control can be found in many books and textbooks, a recent one is Hughes and Drury (2013).

2.1 Open Loop Motor Identification

The first step in designing the control loops described above is to create a mathematical model of the open loop stick dynamics. Usually a model of the system can be built using physical and electrical parameters found in the motors and gearbox datasheets; unfortunately in our case, no details were available on the motors except the power supply voltage (24 V). Thus, model identification is necessary. Essentially two branches of linear model identification exists: time-domain and frequency domain. Frequency domain techniques excite the system using an input signal characterized by a wide frequency spectrum and estimate the system frequency response function from the measured system output. Application of a frequency domain technique in our case was not viable because open-loop excitation of the DC motor, due to its unavoidable electrical and mechanical asymmetries, was found to always lead to a drift in the shaft position making the stick likely to hit a hard stop before the end of the test. Thus we used a time-domain method: step response fitting. Excitation of the motor with a voltage step revealed much easier and safer to implement; actually a voltage doublet (two successive steps of same amplitude but different signs) were employed to have the stick remain well inside the hard stop limits.

It is now convenient to introduce a basic mathematical model of a brushed DC motor with a load of know inertia. Given the motor input voltage V, and the two measured outputs: current I and shaft (stick) angular position θ, the dynamic model can be described by the following set of differential equations:

$$\begin{aligned} V &= L\dot{I} + RI + K_b\dot{\theta} \\ J\ddot{\theta} &= K_t I - D\dot{\theta} \end{aligned} \tag{1}$$

were L and R are armature inductance and resistance respectively, K_b and K_t, usually very similar in value, are the motor back-EMF and torque constants, J is the load inertia and D is a dissipative coefficient that models friction at the shaft. Note the term $K_t I$ that shows how motor torque is linearly proportional to motor current I.

Going from time to Laplace domain, and rearranging yields the electrical and mechanical transfer functions of the DC motor:

$$\begin{aligned} \frac{I(s)}{V(s)} &= G_e(s) = \frac{Js + D}{JLs^2 + (JR + DL)s + DR + K_b K_t} \\ \frac{\theta(s)}{I(s)} &= G_m(s) = \frac{K_t}{Js^2 + Ds} \end{aligned} \tag{2}$$

These equations served as guideline for selecting an appropriate process model for the identification phase. A set of voltage doublets were applied on both motors to identify the two motors separately, then a least square optimization process was run to obtain two transfer functions with the same mathematical structure of Eq. 2 which best fit the experimental step response. The identified model transfer function is (roll axis only):