Hybrid voice coil actuator with novel high-precision force control device based on incremental sensors

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Abstract

With the emergence of more complex, intelligent mechatronic devices a need for innovative types and techniques of ultra-precision positioning solutions arises. Hybrid actuators have been developed to combine long stroke capability with extremely accurate positioning and tracing performance, previously only available for short distance travel ranges. Successful implementations integrate drive concepts such as piezo modules, spindle drives and voice coil actuators, operated in closed-loop with one position feedback sensor (MISO Systems) [1]. In addition to measuring physical dimensions and distances, a need for high-precision, integrated capabilities with regard to interacting with innovative mechatronic devices occurs. In this paper, a hybrid actuator concept, consisting of a long stroke voice coil drive guided by linear bearings and a flexure-guided force sensor, both based on independent high-resolution incremental sensors, is presented.

1. Introduction

A linear guided voice coil actuator combines high precision positioning capabilities with long stroke. Additionally, a voice coil actuator force provides a nearly linear relationship with the electric current running through it. Based on the well-known force constant k_F of the design, acting forces can be established in open loop control mode. Considering high resolution force generation demands, the friction of the mechanical linear guide $(F_R > \pm 0.1N)$, imprecise values of k_F as well as a nonlinear behaviour of k_F can cause issues and make such voice coil systems unsuitable for highly accurate force generation in open loop mode.

A solution for this problem was found in an additional monolithic flexure-hinge guided force sensor capable of generating frictionless motion based on a high-rigidity joint design. Thus, precise external force measurement is enabled by measuring the displacement of the passive force transducer using nanometer-level resolution, incremental positioning sensors. In combination with a control loop as shown in Figure 1 closed loop force control is established. Figure 1 illustrates the basic hybrid actuator design. The advantage of such a concept and its integrated control scheme are high resolution positioning capability $(\Delta x < 0.1 nm)$ combined with large stroke $(20 mm)$ as well as high resolution, frictionless force sensing $(\Delta F < 0.005 N)$. The system can be used in trajectory controlled smooth motion and force generation applications, for example the calibration of force sensitive input devices (displays), the automation of bonding processes or to manipulate breakable and delicate goods even in industrial environment.

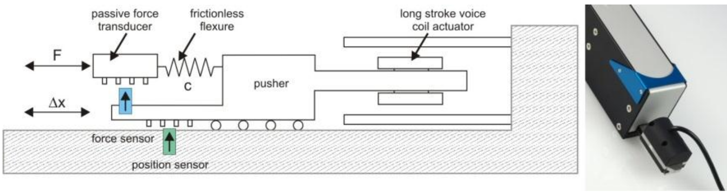

Figure 1: Hybrid Voice Coil Actuator with High–Precision, Frictionless Force Sensor and Long Stroke Positioning Range with Nanometer Resolution.

The main focus of the paper deals with the design of advanced control concepts for such SIMO systems (one actuator combined with two sensors) and their possibilities in industrial applications, especially from the users' point of view. The underlying control loop and the process of switching continuously between position and force control are explained in detail. Looking forward, further conclusions with regard to MIMO systems and their fields of applications will be discussed.

1.1 Force Sensor Design

The force sensor uses high optical resolution sensor combined with frictionless flexure hinges. The resolution of the optical measurement circuit is ∂x. With a predefined or required force resolution ∂f and a given or assumed maximal outer force f_{Max}, the required minimal flexure hinge deflection Δx is given by:

$$\Delta x = \frac{\partial x}{\partial f} \cdot f_{Max} = \frac{1}{c} \cdot f_{Max} \cdot$$

As an example, the PI V-273.431 Voice Coil Actuator includes a frictionless force sensor as shown in Figure 1 with a travel range of 200µm, capable of measuring forces up to 10N with $\partial f = 0.005N$ and a force sensor stiffness of $c = 50N/mm$.

2. General Position, Force and Impedance Control Scheme

Figure 2 shows the control structure of the hybrid system including both position and force feedback control loop. Using given variables K_1, K_2 and K_3 as well as different control laws it is possible to define different, application - specific control strategies for the hybrid voice coil actuator.

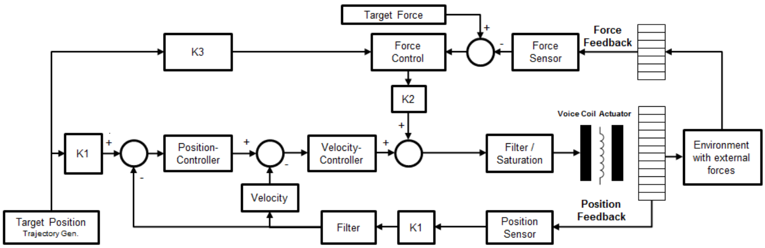

Figure 2: Control Scheme of the Hybrid Voice Coil Actuator

2.1 Position and Velocity Control Mode

Setting $K_1 = 1$ and $K_2 = K_3 = 0$, the control scheme acts in position control mode with overlapped velocity controller. In combination with the force constant k_F of the voice coil actuator, open loop force control is possible. Measuring the required current during position control enables the system to estimate external forces, a distinction between internal friction and external forces is not possible.

2.2 Force Control

Force control mode is used in applications in which interaction forces are not negligible. The given system of Figure 1 is able to apply forces with very high accuracy and enables force control mode by setting $K_1 = K_3 = 0$ and $K_2 = 1$, see Figure 2. The information of the frictionless force sensor is used to control the position and dynamic of the actuator. Internal actuator specific friction is invisible for the force controller. Fields of applications for high-precision force control mode can be found within medical, biological and biochemical technologies, controlling machine tools, automated testing environment as well as safety critical human-robot collaboration.

2.3 Impedance Control

Operational surroundings in industrial applications may be considered as source of disturbances. In case of given dynamic interactions with its environment, an actuator cannot be treated for control purposes as an isolated system. Automated test equipment for navigation devices, mobile phone displays and tablets as well as surface scanning within scanning probe microscopy are applications in which an actuator with high resolution positioning sensor and force (tactile) feedback is in desired contact with its environment. In such safety-critical applications control of position or force alone is inadequate due to given but unknown conditions. By using impedance control mode it is furthermore possible to control the dynamic behaviour of the actuator while interacting with the environment. If $K_1 = 0$ and $K_2 = K_3 = 1$ the target force of Figure 2 is set to zero (Figure 3) it is possible to design the force control law as impedance controller. Due to the fact that the actuator is capable to measure external forces and its position, he is able to act as soft and flexible spring with programmable and adjustable mass, damping and force constant characteristics:

$$F = m\ddot{x} + d\dot{x} + cx \rightarrow \ddot{x} = \frac{F - d\dot{x} - cx}{m} .$$

Including such kind of a tactile feedback, the linear long stroke actuator is able to perform enhanced functions with application-specific stiffness parameters.

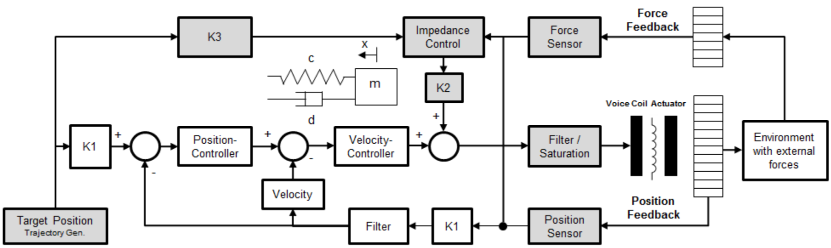

Figure 3: Impedance Control including position and force feedback

References

[1] R.Gloess, “Sub nanometer precision hybrid positioning systems for vertical inspection tools”, ASPE Conference Berkeley, 2008