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Research paper

Dynamic modeling of a 2-dof parallel electrohydraulic-actuated homokinetic platform

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ABSTRACT

Thrust vector control (TVC) is used to control the attitude of spacecraft. The most widespread method to connect the nozzle assembly and rocket consist of a gimbal joint in the case of liquid-propellant or a flexible bearing in the case of solid-propellant. Traditionally, two electrohydraulic linear actuators that are controlled by servovalves tilt the rocket nozzle. However, in this work, TVC is treated as a robotic system and the connection between the platform and the fixed base is achieved using a constant velocity joint. Instead of a servovalve, a novel proportional digital hydraulic valve is proposed. The position feedback is provided through a real-time attitude estimation based on the orientation matrix by using an inertial measurement unit (IMU). Platform kinematics modeling is performed. Dynamics modeling is developed using Newton-Euler formulation. Hydraulics modeling is presented with the description of the electrohydraulic system. Due to the linear behavior of the control valve, a simple pure proportional controller is considered. An experimental validation showed that the proposed system achieves good position tracking without instabilities.

1. Introduction

In this paper, a two degrees of freedom (2-dof) parallel platform with two electrohydraulic actuators (EHAs) is developed for thrust vector control (TVC). TVC has been widely used for the attitude control of aircrafts [1]. In the TVC application, two hydraulic or two electromechanical actuators are usually used to deflect the rocket nozzle [2]. This deflection generates a moment that acts on the aircraft to control its attitude [3]. Aerospace applications require a high power density, high dynamic performance, robustness and overload capacity; hence, EHAs are a common choice [4]. An EHA system is composed of a valve to modulate the fluid flow rate based on an input signal and a hydraulic cylinder that converts the flow rate into linear displacements [5]. The TVC system must orient the nozzle on a desired trajectory for the vehicle and maintain the controllably during disturbances. Gust and shear wind are the main disturbances [6]. When using liquid propellant to steer a vehicle along its trajectory, a gimbaled thrust engine is the most common option [7].

In this work, a low-cost EHA platform is built. Usually, much of the cost of an electrohydraulic servo-system is due to the servovalves. For cost reduction, a novel Proportional Digital Hydraulic Valve (PDHV) is proposed to control the oil flow in the actuator chambers. A hydraulic servovalve requires an expensive super-clean fluid system [8], whereas the PDHV operates using an inexpensive fluid filter system. Another cost reduction is achieved using a constant velocity joint (CVJ)

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with an Inertial Measurement Unit (IMU) instead of a gimballed assembly with two angular transducers. The CVJ choice also reduces the moment on the centerline of the rocket [9].

Lazic and Ristanovic [10] proposed a test bench for a TVC system based on a fixed base robotic system. They have presented an analysis of the kinematics and a control strategy for a gimballed 2-dof parallel platform with two EHAs. Two angular transducers provide the angular position of the gimbal, a real-time DAQ system calculates the actuators position for the control algorithm, and two hydraulic servovalves receive the analog signal from the controller. Their experiments show a good position tracking.

Wekerle [6] presented the requirements of an actuation system for TVC systems and presented in [11] a 2-dof mockup of a rocket motor nozzle with two EHAs. The actuators performances are identified in a mass-spring test bench.

Ghosh et al. [12] developed a 2-dof parallel hydraulic actuated system for a heave-and-pitch motion simulator. Two low-cost commercial solenoid proportional valves control the hydraulic actuators. These types of valves have a dead-band and non-linear behavior [13]. Ghosh et al. have considered different types of controllers, and the self-tuning fuzzy proportional–integral–derivative (PID) with bias control showed the best performance. The PID controller was found to have the worst response [12].

Yu et al. [14] developed a novel rotary spool direct drive servovalve with axisymmetric flow. Experiments and computational fluid dynamics (CFD) simulations show the reduction of forces on the valve spool.

The angular position estimation of an IMU is a common topic of research, with the variations of the Kalman filter (KF) representing the most common option for sensor fusing between accelerometer and gyroscope data [15–17]. Accuracy improvements are achieved if the physical constraints are considered during the angular position estimation [18–19]. KF is able to model the noise of the IMU and obtain an optimal estimation of the attitude [20]. However, these stochastic approaches of the KF require a recursive calculation, making its real-time implementation unacceptable for low-cost hardware. A frequency-based approach, for example, a complementary filter (CF), requires a smaller computational cost [21]. In a CF, the accelerometer data passes through a low-pass filter and the gyroscope data passes through a high-pass filter. The KF and CF have a maximum angular error of approximately less than 1° for most of the applications [22–26].

Pennestrí et al. [27] conducted a kinematic analysis and a numerical simulation of a CVJ with geometric errors. Kimata et al. analyzed the CVJ dynamics by taking into account the friction between moving parts [28]; furthermore, the results are validated with simulations and experiments [29]. These works focus on the powertrain problem.

In the present work, the platform developed is similar to that of Lazic and Ristanovic [10]; however, a CVJ with an IMU is used instead of a gimbal with two rotary encoders and a novel PDHV is used instead of commercial servovalves. These differences reduce the system cost by more than one order of magnitude. The proposed controller is a simple proportional (P) controlled controller; however, it has an improved performance compared with the controller of Gosh et al. [12] because of the linear behavior of the PDHV. Accelerometer and gyroscope sensor data fusion is performed using a CF considering the kinematic constrains of the CVJ. In addition, the CF is based on attitude matrices (usually called rotation matrix) instead of quaternions, Euler angles, or Cardan (Tait-Bryan) angles, which are the typical choices.

In this paper, first a kinematic description of the platform is presented. Hence, in the dynamic modeling, a full analysis is performed using the Newton-Euler formulation to obtain the equations of motion. The system model consists of the dynamic model of the platform, a proposed model for the hydraulic system and the proportional controller model. The method to calculate the attitude of the platform from accelerometer and gyroscope data is depicted afterwards. Finally, the simulation and experimental results are shown, also validating the system operation, and then, some concluding remarks are presented at the end. Fig. 1 shows an overview of the platform.

2. Kinematics

Fig. 2 shows the kinematic scheme of the parallel two degrees of freedom platform (2dof) with a load. One of the shafts of the constant velocity joint (CVJ) is fixed to the fixed base, and the other shaft is attached to a moving platform. Point B is the center of the fixed base, and O is the center of the CVJ. Universal joints connect the hydraulic actuators to the base, and ball joints connect it to the platform. Points C_{31} and C_{32} are the centers of the actuators ball joints. C_{21} and C_{22} are the centers of the actuator universal joint crossheads. P and L are the centers of mass of the moving platform and load, respectively. C is the center of the top surface of the moving platform.

Two references frames are defined: F is fixed to the base and S is attached to the moving platform. The rotation between the frames are summarized by the following indication,

$$\underset{\substack{Fixed\\Base\\(x,y,z)}}{F} \xrightarrow{\theta(\boldsymbol{p})} \underset{\substack{Moving\\Plat\,form\\(x',y',z')}}{S}$$

where p is the Euler vector and θ is the angle of rotation around p, which superposes F and S.

Angle θ is the angle that tilts the platform, i.e., the angle between OC and the vertical. The position of p changes in the fixed (x, y) plane and can be written as follows:

$$\boldsymbol{p} = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 \end{bmatrix}^T, \quad (1)$$

where φ is the angle between vector $\boldsymbol{p}$ and the x-axis.