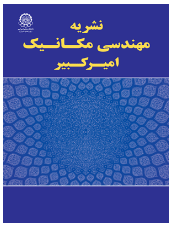

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Hybrid Position and Force Control for a Spherical Inverted Pendulum Connected to a Quadrotor in a Constrained Motion

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ABSTRACT: Today, the use of drones to automate activities such as civil works, rescue operations, and military missions is expanding to increase speed and accuracy, retaining manpower and reducing costs. According to this approach, in this paper, hybrid control of position and force for a spherical inverted pendulum on top of a quadrotor whose motion is constrained in the vertical direction is studied to enable the quadrotor-spherical inverted pendulum system to perform operations such as painting and cleaning on high ceilings. In this regard, first using Newton-Euler laws, the equations of motion governing the quadrotor-inverted pendulum system in the constrained motion are extracted, and then by presenting a model for the constraint force, a hierarchical control system including position-force control loop, inverted pendulum orientation control loop and quadrotor orientation control loop is provided. Proposed Control laws for the inverted pendulum orientation control loop and the quadrotor orientation control loop are designed using some theorems of geometric control methods. Finally, to study the performance of the proposed control method, some numerical simulations have been performed.

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1- Introduction

In recent years, Unmanned Aerial Vehicles (UAVs), specially quadrotors, have attracted the attention of scientists for performing various tasks autonomously. cleaning or painting high ceilings are examples of tasks that can be performed by the quadrotors. In this study, the possibility of painting and cleaning high ceilings with a quadrotor without adding any actuator via control of an inverted spherical pendulum connected to it has been studied. According to the nature of the mentioned operations, the path of the end of the inverted spherical pendulum, which is actually the location of the painting or cleaning tool, and the force applied from it to the ceiling should be controlled. Many researchers have studied the problem of inverted pendulum control on top of a quadrotor [1-5] but none of them has not proposed a control law for a pendulum in a constrained motion such as the operation considered in this study.

Unlike previous studies, in this study, the pendulum is in contact with a rigid horizontal ceiling, and according to the intended mission, the problem of hybrid control of the horizontal path of the end of the pendulum and the force entering the ceiling has been studied. In other words, the main innovation of this study is the modeling of the quadrotor and pendulum system in contact with a rigid horizontal ceiling, as well as the design of the hybrid force and position controller for the end of the pendulum.

2- Methodology

First, a mathematical model is derived for the dynamics of the quadrotor-inverted pendulum system when the pendulum is in contact with a horizontal rigid ceiling (Fig. 2).

The equations of the motions in the model have been derived from Newton- Euler method while the dynamics of the rotors are adapted from previous studies. Moreover, to model the force acting on the pendulum by the ceiling f_N, the pendulum is considered as a mass attached to the roof by a spring (Fig. 3).

Then, a hierarchical control scheme is proposed to control the position and force of the pendulum. The control system has three control loops. The outer loop calculates the desired orientation of the connecting rod of the pendulum and desired component of the thrust force of the quadrotor in the direction of the rod. The median loop computes the desired attitude and thrust force of the quadrotor according to the outputs of the outer loop. Finally, the inner loop controls the quadrotor attitude to track its desired computed value. The control loops are designed by backstepping and a simplified model of the system. Geometric error functions are implemented to design the median and inner loops to avoid possible singularities. The stability of the control loops is proven by some theorems of the geometric control literature.

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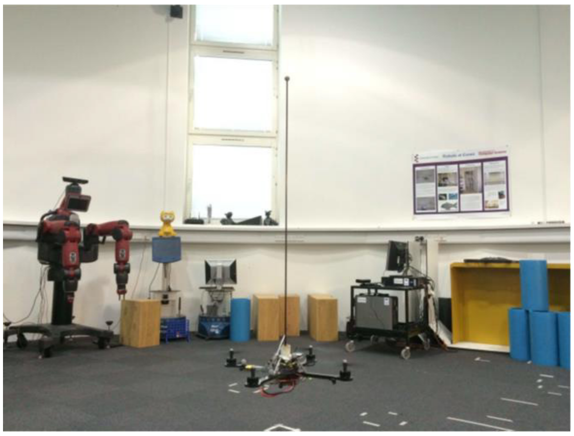

Fig. 1. Quadrotor-inverted pendulum system [5]

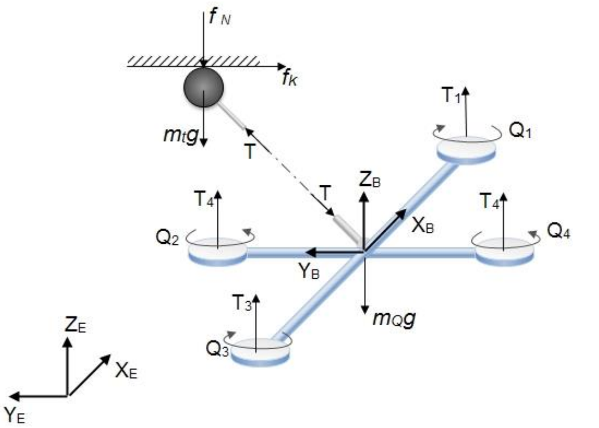

Fig. 2. Free diagram of the forces and torques for quadrotor-inverted pendulum system in a constrained motion

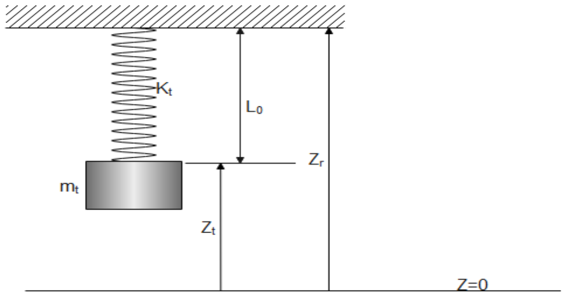

Fig. 3. Schematic of the model of the pendulum- ceiling interaction

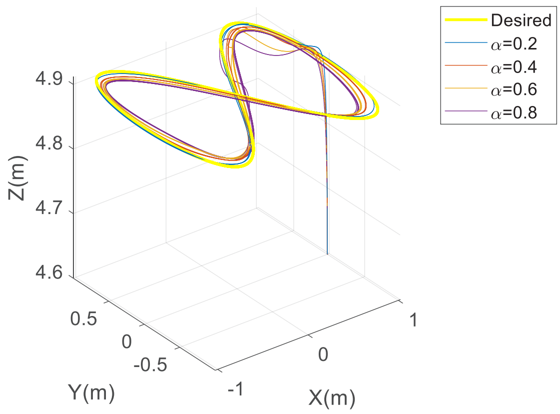

Fig. 4. Pendulum paths while tracking the desired trajectories vs the desired path.

3- Results and Discussions

To verify the effectiveness and robustness of the proposed control scheme some simulations have been done. In all of the simulations, a quadrotor is desired to track an eight-shape path with different velocity trajectories. Moreover, the perfect model of the system is implemented in simulations to assess the performance of the controller. Also, to fairly simulate the performance of the controller, the sampling rate is selected equal to 500Hz and a time delay of about 10ms is enforced on all of the measurement channels.

In the first simulation, there is not any disturbance acting on the system and just the performance of the controller has been evaluated. Simulation results show that although the pendulum tip is not on the path initially, it tracks the desired trajectory with a reasonable error even if the velocity of the trajectory is higher than its nominal value for which the controller has been tuned (Fig. 4).

The tracking errors are due to the simplifications made for driving the design model and the transportation delay of the measurements. Furthermore, the desired force of the pendulum and the yaw angle of the quadrotor has been tracked by implementing the proposed control scheme.

In the second simulation, the robustness of the control system against disturbances is evaluated. Therefore, a horizontal step force disturbance has been applied to the quadrotor. The results of the simulation show that despite the disturbances, the pendulum tracked the desired trajectory of its position and force successfully.

4- Conclusions

In this paper, a geometric nonlinear hierarchical controller is presented for the hybrid control of the path and force of a spherical inverted pendulum connected to a quadrotor whose vertical movement is constrained by a horizontal surface. Using the theorems presented in the geometric control literature, it was shown that this controller can provide the stability of the pendulum position and the force acting on it from the surface, the direction of the connecting rod, and the attitude of the quadrotor. The results of numerical simulations with a complete model of the quadrotor and simulation of data sampling with a constant rate and with a time delay show that the presented controller, despite the time delay of data transmission and the simplifying assumptions made for its design, can maintain the stability of the pendulum on the desired trajectories and providing the desired force. Of course, despite maintaining the stability of the system on the paths with higher speeds, the efficiency of the controller decreases, which is due to the limitation of the bandwidth of the actuators and the increase in the effect of the terms related to the gyroscopic moment and the inertia of the rotors which are neglected in control design. In addition, the simulation results show that the controller is robust to environmental disturbances on the quadrotor. Future research will include more complete modeling of the quadrotor-pendulum system, adaptive controller design to estimate the friction coefficient and spring constant of the equivalent pendulum, and practical implementation of the presented controller. In addition, the design of a tracking differentiator to calculate the derivatives of inter-loop control parameters to improve the performance of the controller may be studied.

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