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# Nonlinear Intelligent Fault-Tolerant Control of Quadrotor-Based Aerial Manipulators for Precision Agriculture Applications

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**Abstract**

An aerial manipulator, that is an aerial robot such as a quadrotor, endowed with a robotic manipulator, can extend the application of aerial robots by allowing the aerial robot to physically interact with objects. For example, in precision agriculture, autonomous, accurate and fault-tolerant control (FTC) of the aerial manipulator is important to allow the aerial manipulator to collect viable plant samples without causing damage to the plant. Quadrotors are, however, challenging to control as they are underactuated, and have coupled, nonlinear dynamics. The control of quadrotor-based aerial manipulators is further complicated due to the coupling between the motion of the manipulator and that of the quadrotor. In this study, an intelligent, nonlinear FTC for quadrotor-based aerial manipulators is developed. Both active and passive sliding mode FTCs are investigated. The passive FTCs rely on the robust properties of the sliding mode controllers (SMCs) to mitigate rotor faults. For the active FTCs, different static neural network structures are investigated for the fault detection and diagnosis (FDD) unit used to detect and measure rotor faults. Several different SMC formulations are investigated in this study, including; continuous and discontinuous SMCs, integral SMCs, adaptive SMCs, and super-twisting SMCs. SMCs typically suffer from the undesirable chattering phenomena, which can be observed as high-frequency oscillations of the controlled system. A novel chattering index is therefore developed to measure the chattering levels of SMCs. When tuning the controllers' gains, the objectives are to minimise the trajectory tracking error, control input, and chattering. Manual tuning of controller gains, taking into account multiple conflicting objectives, is time consuming and does not result in optimal gains being selected. In this study, two intelligent multi-objective optimisation (MOO) algorithms, the multi-objective particle swarm optimisation (MOPSO) algorithm and a multi-objective genetic algorithm (MOGA) are compared for the SMC gains tuning. The novel chattering index is used as the chattering minimisation objective, together with trajectory tracking error and control input minimisation objectives, when tuning the SMC gains using the MOPSO controller gains-optimisation method. Simulations are conducted for the FTC of a large aerial manipulator with a two degree-of-freedom (DoF) manipulator. The simulation results show that the aerial manipulator successfully performs farm coverage for remote sensing while collecting plant samples, in the presence of a rotor fault. Laboratory experiments of a miniature aerial manipulator, including manipulator motion in the presence of a rotor fault, are conducted. The miniature aerial manipulator used is a Crazyflie quadrotor with an optical flow deck for position feedback and a one-DoF manipulator actuated by a servo motor. The simulations and experiments show the effectiveness of the passive and active sliding mode FTCs, the neural network-based FDD units, the intelligent MOO controller gains-tuning method, and the developed chattering index.