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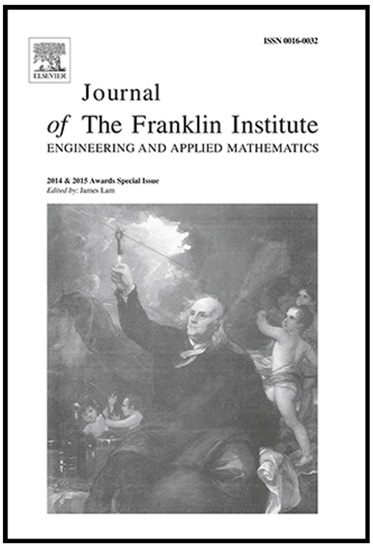

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Intelligent Attitude and Flapping Angles Estimation of Flybarless Helicopters Under Near-hover Conditions

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Abstract **—Inaccuracy of measurements, associated with most of the commercial-off-the-shelf (COTS) Inertial Measurement Unit (IMU), impede achieving an accurate attitude estimation during autonomous near-hover flight. Moreover, the unmeasured states of the Tip Path Plane (TPP) flapping angles of the main rotor make the estimation and control of unmanned helicopters more challenging. In this paper, an intelligent adaptive fuzzy data fusion algorithm is designed to obtain more accurate estimates of the attitude and flapping angles for a flybarless miniature helicopter. In this algorithm, the filter's measurement noise matrix is continuously adapted using the Innovative-based Adaptive Estimation (IAE) technique. This technique is based on evaluating the discrepancy between the actual and theoretical covariance of the filter's innovation sequence. A well-tuned multi-input, single output Fuzzy Inference System (FIS) takes the value of this evaluated discrepancy and its rate of change as inputs and provides the required adjustment value as an output based on a set of predefined fuzzy rules. Compared to the conventional Kalman Filter (KF) state estimation results, the proposed intelligent estimation results have demonstrated an obvious enhancement in estimating the attitude and the flapping angles. The estimated flapping angles have been also used to estimate the moments and forces of the helicopter rotors under near-hover assumptions. An actual near-hover flight was conducted to validate the performance of the proposed intelligent estimation method.**

Index Terms— Unmanned Aerial Vehicle (UAV); Flybarless Helicopter; Adaptive Fuzzy Kalman Filter; Attitude Estimation; Flapping Angles Estimation; Rotor Moments and Forces Estimation.

I. INTRODUCTION

UNMANNED miniature helicopters are famed for being viable candidates for several civil and military missions. However, achieving successful autonomous missions depends on the robustness of the controller design, the accuracy of the onboard commercial off-the-shelf sensors and the effectiveness of the sensor fusion algorithm [1, 2, 3, 4, 5]. In the last few decades, there has been an increased awareness of the importance of developing high-accuracy sensor fusion algorit-

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-thms fusion algorithms for state estimation [6, 7] . Thus, several innovative architectures have been proposed in the literature [8, 9, 10, 11, 12]. Incorporating these architectures with complex dynamic models such as UAVs enhances the capability of vehicles to perform flights that demand high degree of autonomy [9, 13, 14, 15]. This incorporation is improved as long as new sensor fusion designs are devised.

Acquiring precise attitude estimates is essential for UAV to boost its maneuverability while autonomous flight is being carried out [16, 6, 17]. Nevertheless, it is challenging to obtain accurate attitude estimates of a vehicle because of problems associated with the low cost onboard sensors, i.e., large drifts, immense noise and measurements biases [18, 19, 20, 21, 22]. These low cost sensors are yet preferred in UAVs due to their compact size, small weight and low power consumption [23]. Attitude estimation approaches, based on fusing the measurements of different low cost sensors, are currently used to compensate for the sensors' course accuracy and thus obtain accurate attitude estimates.

Different approaches have been used to estimate the attitude states; among them are the strapdown approach and the bi-vector approach. The strapdown approach integrates the angular rates to yield the Euler angles; whereas, the bi-vector method estimates the attitude using the measured vehicle's acceleration and magnetic field from the accelerometer and the magnetometer sensors [24]. However, each approach has some disadvantages. A major disadvantage of the strapdown approach is the accumulation of the error due to the integration of the angular body rates. This accumulation of the error increases as the flight time increases due to the inaccuracies associated with the measurements. This may result in an inaccurate attitude estimation. In the bi-vector approach, the vibration of the UAV rotors affects the measurement of the accelerometers and thus leads to an inaccurate estimation of the attitude.

A number of published studies have addressed the problem of the attitude estimation techniques for small-scale helicopters using different low cost sensor fusion techniques. Using a Kalman filter, the pitch and roll angles are estimated based on the data fusion between the Global Positioning System (GPS) and the gyro measurements [25]. An unscented Kalman filter was used in [26] to estimate the attitude and the position of a tethered, unmanned miniature helicopter using