Effects of unmodelled dynamic factors on an under-actuated quadrotor: A review of hybrid observer design methods

Ghulam E Mustafa Abro1, Vijanth Sagayan Asirvadam1, Saiful Azrin Bin Mohd Zulkifli1, Abdul Sattar2, Dileep Kumar3 and Ali Anwer4

Abstract
Unmodelled dynamic factors are either the left-over or the estimated factors such as lower or upper bound values while modelling any mechatronic system. Hence, with the inclusion of under-actuation in a system such as fewer number of actuators as compared to degrees of freedom, this will lead the system to high instability. These factors are changing instantly during multiple flights of quadrotor that is, the values of these factors in path following may vary from the values in hovering mode. Hence, it is one of the strenuous tasks to tackle these unmodelled dynamic factors for the multiple flight modes of an underactuated quadrotor craft. One of the better ways for tracking control of a quadrotor aerial vehicle with unmodelled dynamics is to observe and estimate the instant change in parameters. Thus, this paper exhibits an extensive review of several hybrid observer design methods being fused with some novel control strategies. In addition to this, the survey paper also summarises the limitations of the current state of the art approaches. This paper demonstrates an unexplored field of study where researchers must need to evaluate the performance of hybrid observer design methods.

Keywords
Unmodelled dynamics, estimator, underactuated, UAV, lower and upper bounds

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Introduction
Since the literature is crammed with the study of robust, adaptive and adaptive-robust control designs for operating the quadrotor in multiple flight modes with aggressive manoeuvres. Most of these controllers provide trade-off results for unmodelled dynamic factors thus, researchers opt hybrid control strategies for better tracking performance. These hybrid controllers provide compromising results even after being fused with different observer designs. The researcher must compromise on several things such that chattering phenomenon (high oscillations at rotors) due to switching in between control sub-blocks, transient and steady-state errors, delay in accelerations and lastly tracking errors.

The taxonomy of this paper is partitioned into six sections. Firstly, one may understand the aim and objective of this paper through an introduction. The second section of the dynamic model addresses some ordinary differential equations of the quadrotor. Thirdly, limitations of previously discussed research contributions are stated under the section of Literature Review. Under the fourth section of technical issues and analysis, one may find exactly the discussion about the compromising results. With the support of technical analysis; one may be assisted to explore several aspects in this area. Lastly, the whole idea of the paper is summarised with a comprehensive conclusion.

1Electrical and Electronic Engineering Department, Universiti Teknologi PETRONAS, Seri Iskandar, Perak, Malaysia
2School of Engineering, RMIT University, Melbourne, Victoria, Australia
3State Key Laboratory of Industrial Control Technology, Zhejiang University, Hangzhou, Zhejiang, China
4Quaid-e-Awam University of Engineering Science and Technology, Nawabshah, Pakistan

Corresponding author:
Ghulam E Mustafa Abro, Electrical and Electronic Engineering Department, Universiti Teknologi PETRONAS, Seri Iskandar, Perak 32610, Malaysia.
Email: Mustafa.abro@ieee.org

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Fully versus underactuated systems

There are two popular methods to derive equations of motions namely Newton Euler and Lagrangian formulation techniques. The Newton Euler method defines the equation of motion with the help of the second law of motion and in terms of force and momentum. The Lagrangian method provides the system’s behaviour in terms of net energy. The idea behind both formulations is to acquire the set of equations that defines the motion. Consider the general equation of an actuated system,

\[ D(q)\dot{q} + C(q, \dot{q})\dot{q} + G(q) = F(q)u \]  

(1)

The provided equation (1) is the general equation that can be used for both fully actuated and underactuated systems where \( D(q) \in \mathbb{R}^{nxn} \) is the inertia matrix, \( C(q, \dot{q}) \in \mathbb{R}^{n} \) represents centrifugal terms and \( G(q) \) denotes gravity. The term ‘\( \dot{q} \)’ \( \in \mathbb{R}^{n} \) is the configuration vector, \( u \in \mathbb{R}^{m} \) is known as the actuator input vector. Thus, the term \( F(q) \) will be a non-square matrix given as in equation (1). Discussing the fully actuated system is a control system in terms of the configuration of \( (q, \dot{q}, t) \) if and only if it can command an instant change in acceleration in an arbitrary direction in \( q \) which means that:

\[ \text{rank}(F(q)) = \text{dim}(q) \]  

(2)

whereas an under-actuated system can be defined in same way, but it has no ability to command an instant change in acceleration in arbitrary direction in \( q \) which means that:

\[ \text{rank}(F(q)) < \text{dim}(q) \]  

(3)

In simple words one may conclude that a system can be said as an under-actuated system if its external forces are unable to exert an acceleration to its states in all directions or a system that cannot follow the arbitrary trajectories. One can say that the input matrix \( F(q) \) as shown in equation (1) depends on the states of the system and thus it results an underactuation depending directly on the system states. One can know the complexity of underactuated system by its degree of underactuation as illustrated below:

\[ \text{dim}(q) - \text{rank}(F(q)) = \text{Degree of underactuation} \]  

(4)

Underactuated quadrotor model

System that is by-default underactuated such as quadrotor, is highly unstable dynamic system. It is underactuated because of 04 control inputs and six degree of freedoms (DOF). These systems have low cost, low maintenance and less power consumption and with the induction of unmodelled dynamic factors it becomes much difficult to stabilise it in specific flight mode. As far as its construction is concerned, it has been modelled in a cross configuration with symmetrical arms that provides the centralisation of the payload. The system state variables are controlled using thrust, roll, pitch and yaw and these are directly dependent on the velocities of every propeller. Even after being highly unstable system, it is believed that certain control designs can stabilise it to attend a certain altitude and attitude subsequently.

It is studied that the equations of motion, aerodynamic forces and input turning effect (torque) are obtained through body frame of reference which is non-inertial frame too whereas the other one is earth frame of reference or known as inertial frame of reference. These two reference frames are used to define the motion of underactuated quadrotor. The earth inertial frame of reference is denoted by (E-frame) and symbolised by \((O_E, x_E, y_E, z_E)\) where \(O_E\) is defined as axis of origin and \((x_E, y_E, z_E)\) are defined as North West and configuration with respect to earth. By using this E-frame one can see the linear positions of gravity as denoted by \(g\) and the ZYX Euler angles \(\Theta\) are defined in Figure 1.

Moreover, the B-frame attached to the quadrotor body is right hand reference frame and it is denoted as \((O_B, x_B, y_B, z_B)\) where \(O_B\) is defined as axis of origin and coincides with the centre of cross structure of quadrotor. The directions in this frame are denoted as \(x_B, y_B, z_B\) towards front, left and up, respectively. The B-Frame defines the linear velocity \(v\), the angular velocity \(\omega\) and the torque as \(\tau\). The linear positions can be determined using a simple vector in between E-Frame and B-Frame. The Euler angles \((\Theta = [\phi \theta \psi])\)
representing the attitude [Roll, Pitch and Yaw] respectively which are defined by B-Frame with reference to E-Frame. This can further help in developing the rotation matrix to map the orientation vector from B to E Frame and it is given as:

\[
R = \begin{bmatrix}
    c_\theta c_\phi & -c_\phi & s_\phi s_\theta & c_\phi s_\theta \\
    c_\phi s_\theta & c_\phi & s_\phi c_\theta & -c_\phi c_\theta \\
    -s_\theta & 0 & c_\theta & 0 \\
    0 & -c_\phi & s_\phi c_\theta & c_\phi c_\theta \\
\end{bmatrix}
\]  

where \( s_x = \sin(x) \) and \( c_x = \cos(x) \) in provided rotational matrix as shown above in equation (5). One may use this transfer matrix in order to build a relationship in between the E-frame and B-frame as shown:

\[
\dot{\Theta} = T_\omega, T = \begin{bmatrix} 1 & s_\phi t_\omega & c_\phi t_\omega \\ 0 & c_\phi & -s_\phi \\ 0 & s_\phi/c_\phi & c_\phi/s_\phi \end{bmatrix}
\]  

where \( t_\omega = \tan(\omega) \), it is further observed that any unmanned aerial vehicle (UAV) either quadrotor usually controlled at their nearest equilibrium state because this is the state where it has all Euler angles such that roll, pitch and yaw are less than 15° and therefore the equation (9) can be further simplified as \( \dot{\Theta} = \omega_c \), whereas the transformation matrix is \( T = I_{3 \times 3} \).

This study is compulsory as during modelling one would transforming states from one configuration space to another.

### Literature review

As discussed before, with an inclusion of unmodelled dynamic factors, the practical and precise dynamic model of underactuated quadrotor craft becomes difficult to control even in single flight mode. People have proposed various modelling approaches, but the most common approach of modelling is the Newton Euler formulation. It is a white box modelling and preferred when physical knowledge of the plant is given but the derived model is not completely real. Some researchers also used black box modelling or system identification technique by performing some experiments where any sort of disturbance and time delays can easily be witnessed but it requires complex and costly hardware setup.

By studying different research, it has been observed that the Newton Euler formulation method is most frequent approach (mathematical approach) to derive the set of differential equations. In the same research contributions, the use of smart algorithms is also observed, hybridised with the control designs as one of their sub-control blocks to tackle the unmodelled dynamic factors. These techniques are proposed to acquire the hardly obtained parameters such that payload mass, inertia and wind disturbance etc. with an extensive use of sensors. Thus, the possible approach that can be used in acquiring the realistic model is grey box modelling because of following reasons:

- Physical knowledge of the plant
- Adequate dynamics of process
- Accommodate the sensor-oriented data set.
- Involvement of mathematical approach.

### Hybrid control designs with observer design methods

Since, the objective of this proposal was to investigate the ability of previously proposed algorithms meant for tackling the unmodelled dynamic factors. It has been experienced that there are several research contributions since decade for the topic. Majority of the algorithms follow a trend of merging a control design with some sort of special estimator or observer technique. This sub-section will address all popular techniques for tackling unmodelled dynamic factors and in last conclude the research gap for our proposed research topic.

Starting from the most popular control designs, Proportional Integral (PI) that has been seen, amalgamated with extended Kalman filter to address the exogenous factor that is, wind disturbance on the trajectory tacking of quadrotor but due to the accelerometer’s external noise and insufficient tuning of gains, tracking errors were observed with huge settling time. Backpropagation neural network-based estimation merged with backstepping control design to address the wind disturbance like unmodelled factor again, but deviation of quadrotor has been observed at 33rd seconds in the simulation within finite time of simulation. In the same contribution, memory constraints were also observed that does not accommodate the online data set from inertial measurement unit for further estimation.

In addition to this, Genetic algorithm (GA) with adaptive control design that is, Fuzzy is proposed (Xu Q et al., 2020). The process time due to fuzzy set of rules is comparatively high and some overshoots were also observed during aggressive manoeuvres. The similar approach is observed when two parallel fuzzy model is used with GA where fuzzy set of rules are based on single dimension. This technique reduces the computational time but still the overshoots are there. The techniques like robust compensator and integral square error can be amalgamated with sliding mode control (SMC) or proportional-integral-derivative (PID) technique. The only limitation with these techniques is the settling time hence in this scenario, quadrotor will need much time to stabilise again and follow the trajectory smoothly, whereas chattering effect is observed for SMC design.

In comparison with existing techniques such that disturbance observer, neural network based estimation, fuzzy logic based estimations and nonlinear extended state observer, Linear extended state observer (LESO) is better option because its parameters are easy to tune unlike disturbance observer and high convergence rates as compare to neural and fuzzy...
estimation approaches. It is observed that with the induction of hyperbolic function in the control design for non-smooth disturbances that is, dual loop integral sliding mode control\(^\text{23}\) with LESO provides better estimation but with high settling time and chattering effect. In order to reduce the chattering effect, one may go for below mentioned methods:

- Using high gains of SMC
- Using Super twisting algorithm\(^\text{24}\)
- Chattering can be reduced using Terminal Sliding mode\(^\text{25}\)
- Integral form of SMC (chattering and huge steady state error)
- Use a low pass filter for control input signal

Since individual approaches have some limitations, for instance the issue of singularity with Euler angle approach and sign ambiguity with quaternion restricts the ability of UAV to track the trajectories. Thus, quaternion approach is merged with non-linear disturbance observer designs for upper bound uncertainties. SMC is insensitive to uncertainties but requires estimation or observer designs for upper bound uncertainties. Since the sliding mode is insensitive to uncertainties but requires estimation or observer designs for upper bound uncertainties. SMC design also generates the chattering noise around the sliding surface that degrades the control performance, but this can be reduced as discussed.\(^\text{24,25}\)

For control designs, classical controllers are insufficient for the closed loop performance, model reference adaptive schemes are challenging to develop and for fuzzy based designs detail model information is required hence this results in poor robustness against the unmodelled dynamic factors. Since the sliding mode is insensitive to uncertainties but requires estimation or observer designs for upper bound uncertainties. SMC design also generates the chattering noise around the sliding surface that degrades the control performance, but this can be reduced as discussed.\(^\text{24,25}\)

For slow and smooth disturbances, the backstepping (BS) with nonlinear disturbance observer or ESO have been effective but they are limited for non-smooth disturbances. Discussing further, Predictive Optimal Control design with the use of disturbance observer. The proposed technique is just designed for non-smooth disturbance of payload pick and drop case. The scheme provides robust tracking performance by introducing the integral item \(c_{ii} = 0.5\), further overshoots are observed in the response. This integral item is introduced to minimise the steady state error but as soon as the payload is released, the overshoot increases up to 15%. Operating this quadrotor for long distance it has been observed that the steady state error for speed is 8% with active wind speed of 4 m/s. In case of rotor failure, one of the rotor’s efficiency was reduced up to 20% and it behaves similar as in case of payload.

The brief summary is highlighted in Table 2.

Second technique proposed, is based on dual loop integral sliding mode control (DL-SMC) based linear extended state observer (LESO).\(^\text{23}\) This technique proposes formulation of uncertainties within the kinematic and dynamic model of underactuated quadrotor. Whereas the LESO estimates the smooth uncertainties brilliantly. Hence, with an addition of hyperbolic function LESO has been enabled to estimate the non-smooth uncertainties too but with the addition of this function with SMC, the steady state error and chattering increases. The integral term does not significantly improve the responses. The summary is provided in Table 3.

Third paper,\(^\text{27}\) is based on Predictive optimal control (POC) design with the use of disturbance observer. The POC controller is formulated with a problem of non-smooth disturbance of payload pick and drop case. The scheme provides robust tracking performance by assuming the \([-25\) to \(+25\)] perturbations. There is still room for exploring the algorithm for further perturbations since in Dong et al.,\(^\text{19}\) the work has been done for three unmodelled disturbances and during picking and release of payload with huge perturbations 10% to 15% overshoots are examined already. Moreover, POC provides easy tuning of the parameters of disturbance estimator.

Third order Sliding mode control (TOSMC)\(^\text{33}\) is used with quaternion approach to address the singularity problem and by using high order and low-pass filter for control signal the inherent issue of chattering is removed. The proposed technique is just designed for tackling the unmodelled factors and disturbances in general and no specific discussion is made regarding payload, wind disturbance and rotor efficiency loss.

**State of the art and its limitations**

In the paper,\(^\text{18}\) three unmodelled dynamic factors are considered namely wind disturbance, payload variation and rotor efficiency loss. The approach is based on disturbance observer and control technique has been divided into two sub-control blocks namely proportional-integral for position errors and backstepping technique for velocity errors. It has been observed that with all disturbances there had been delay in the predicted and theoretical accelerations during thrust rise from 2400 revolutions per minute (RPM) to 3200 RPM. Whereas in the presence of payload of 200 g a steady state error of 2% is also observed and by introducing the integral item \(c_{ii} = 0.5\), further overshoots are observed in the response. This integral item is introduced to minimise the steady state error but as soon as the payload is released, the overshoot increases up to 15%. Operating this quadrotor for long distance it has been observed that the steady state error for speed is 8% with active wind speed of 4 m/s. In case of rotor failure, one of the rotor’s efficiency was reduced up to 20% and it behaves similar as in case of payload.

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**Technical analysis and discussion**

Unmodelled dynamic factors and exogenous disturbances with underactuation in quadrotor like unmanned aerial vehicle (UAV) leads it to instability. The proposed techniques provide comparatively fine results within close and open environment including single flight mode and bounded perturbations only. There is still a need to evaluate the estimator or observer performance with suitable control design for robust
| Sr. No | Approach to acquire model          | Control design                  | Estimation technique                  | Limitations                                                                 | Year   |
|--------|-----------------------------------|---------------------------------|---------------------------------------|-----------------------------------------------------------------------------|--------|
| 1      | Newton Euler Formulation          | Proportional Integral (PI)      | Extended Kalman Filter                 | Due to external noise in accelerometer built-in and due to saturation of rotors, the reasonable tracking error was observed. | 2019   |
| 2      | Opted from previous paper         | Backstepping Control Design (BSC) | Back Propagation, Neural Network       | Due to the instant change in unmodelled factor of wind disturbance, the deviation from helical trajectory is observed on regular intervals. | 2019   |
| 3      | Newton Euler Formulation          | Fuzzy Logic Control             | Genetic Algorithm                      | The process time was huge, and overshoots were also observed during aggressive moves. | 2018   |
| 4      | Motion Sensors                    | Fuzzy Logic Control             | Two Parallel Fuzzy Logic Systems       | The tracking errors were minimised but still there were some overshoots.      | 2016   |
| 5      | Opted from paper                  | Proportional Derivative (PD)    | Robust compensator design              | Due to change in wind disturbance quadrotor deviates from trajectory and needs 5 s to follow the trajectory again. | 2017   |
| 6      | Newton Euler Formulation          | H- Infinity Control             | Robust compensator design              | The output response within finite state of time (integral square error) is fine but afterwards the tracking errors are huge, and it deviates the quadrotor. | 2016   |
| 7      | Newton Euler Formulation          | PI for Position error & BS for velocity error | Disturbance Observer (DO)               | The tracking performance with unmodelled factors that is, model mismatch and input delays was observed to be good but with the SSE of 2%. Moreover, with payload the overshoot was also observed. | 2014   |
| 8      | Newton Euler Formulation          | Dual Loop Integral sliding mode control | Linear extended state observer (LESO) | LESCO estimates the uncertainties very brilliantly but the use of hyperbolic function and simultaneously the use of integral SMC introduces higher settling time and chattering. | 2020   |
| 9      | Opted                             | Two PI                          | 4 Equivalent Input Disturbance (EID)  | Simple to use and tune and address the exogenous disturbances. The SSE is reduced but this does not comment over the transient issues. | 2020   |
| 10     | Quaternion method followed without going into dynamics | BSC with                         | Non-linear reference model based on quaternion differential kinematics | Due to small mass of experimental platform such that 65 grams of quadrotor the SSE are small but as size increases the errors may also increase. Whereas in quaternion smooth transitions are done with small gains and for aggressive manoeuvres tuning of gains is required again. | 2020   |
| 11     | Opted and Manipulated with Payload factor | Predictive Optimal Control Design based on receding-horizon feedback correction approach | Disturbance Estimator/observer (DO)   | The tracking performance with unmodelled factor of payload was observed to be good. The parameters of DO are difficult to tune. | 2020   |

(continued)
trajectory performance in terms of delay in accelerations, chattering effect and transient-steady state issues. Critically observed that it is very difficult to tune the parameters of disturbance observer that provides comparatively better results than the extended state observer (ESO) for smooth and non-smooth variations. Furthermore, with an inclusion of hyperbolic tangent functions, ESO becomes suitable for the same case, but this technique estimates the factors with a bit delay that limits UAV for soft manoeuvres only. For control design being amalgamated with observer or estimator, it is observed that dual loop SMC or higher order SMC is highly recommended for above case but here one should compromise either on settling time or steady state error. The higher order SMC addresses the issue in Sanwale et al.33 smartly but discussion of three unmodelled dynamic factors and exogenous disturbances in lumped form is not available. Simultaneously, POC-DE technique is limited to payload variation case only with bounded perturbations.

Thus, this manuscript comes up with further evaluation to address above issues with three frequent unmodelled dynamic factors individually and combinedly such that payload variation, wind disturbance and rotor efficiency loss in open environment for multiple flight modes.

Research motivation

By reading this review paper, one may know the importance of unmodelled dynamic factors based on several modelling approaches. One may include lumped unmodelled dynamic factors in their respective underactuated quadrotor mathematical models to exhibit the real behaviour. Furthermore, all observer-based designs are needed to evaluate further with some predictive learning algorithms for lumped unmodelled factors to obtain comparatively better response.

Based on the discussion so far, this paper comes up with a hypothesis that there is an immediate need to improvise the observers either by hybridising them with any predictive algorithm or may use two hybrid observer designs as proposed in Escobedo-Alva et al.35 The simple understanding can be obtained from the proposed work in Escobedo-Alva et al.,35 where the regulated output is provided to achieve the robust tracking performance of quadrotor with a continuous altitude signal coming from global positioning system (GPS).36,37 One may see the sporadic signal loss due to system malfunctions, obstacles between receiver and satellite signals and above all due to unmodelled dynamic factors. This problem of sporadic signal loss is solved by proposing two hybrid observers-based technique as shown in Escobedo-Alva et al.35

Since now and to the best knowledge of authors, the suitable method to accommodate the payload variation is the Predictive Optimal control (POC) based Disturbance Estimator (DE)27 hence with this
technique if one may use such POC based DE in either cascaded or parallel form just like in Escobedo-Alva et al.\textsuperscript{35} then it may work beyond the perturbations of ±25%. This may resolve the issue for payload variations and wind disturbance. For the robust performance during rotor’s efficiency loss one may hybridise the observer scheme with higher order sliding mode control design as it provides less average error in comparison with Model reference adaptive control and Model predictive control (MPC) technique.\textsuperscript{36}

Similar approach has been observed in de Jesus Rubio et al.\textsuperscript{37} where the proposed strategy is divided into control system that is, position control and attitude control system, each control system is further subdivided into fast and slow loops for angular and translational velocities. In these sub-control blocks author recommended the use of model predictive controller (MPC) with sliding mode disturbance observer design to achieve the robustness in the performance of quadrotor.

This was linear approach hence one can see an explicit nonlinear model predictive control (ENMPC) based on robust sliding mode estimator technique, proposed in Zhu et al.\textsuperscript{40} to accommodate the external aerodynamic disturbances present within the dynamics of quadrotor. This approach is also recommended in Zhu et al.\textsuperscript{40} for formation control design for quadrotor. Since the previous Newton Euler based models were not that complex hence for such models fast scheme of nonlinear model predictive control is suggested along with high gain observers.\textsuperscript{40}

The same technique is used in several ways for the performance evaluation such as in Miladi et al.\textsuperscript{41} where nonlinear information model predictive control (NIFMPC) is proposed for the attitude stabilisation of a UAV in the presence of an external wind disturbance.

| Table 2. Summary of PI and BS based NDO technique.\textsuperscript{18} |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| PI + BS based NDO               | Payload         | Wind disturbance | Rotor efficiency | Any order effect |
|                                 | SE | OS | TS | SE | OS | TS | SE | OS | TS | Delay in accelerations and parameters of NDO are difficult to tune |
|                                 | 2  | 15 | –  | 8  | –  | –  | 2  | 15 | –  |

SE: Steady state error in percentage; OS: Overshoot in percentage; TS: Settling time in seconds.

| Table 3. Summary of DL-SMC based LESO technique.\textsuperscript{23} |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Limitations                     | DL-SMC based LESO | Chattering effect | Estimation delay | Disturbance type | Transient and steady state issues |
|                                 |                 | Yes, on all four rotors | Yes | Smooth and Non-smooth | Either one must compromise in between overshoot or settling time |

| Table 4. Summary of POC-DE approach.\textsuperscript{27} |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Limitations                     | POC based DE    | Chattering effect | Estimation delay | Disturbance type | Perturbations |
|                                 |                 | No              | No              | Smooth and Non-smooth | The results are based on assumptions for perturbations of +25% or –25% in the system while picking and dropping the package. Other factors are not addressed. |

| Table 5. Summary of TOSMC with DO.\textsuperscript{33} |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Limitations                     | TOSMC based DO  | Chattering effect | Estimation delay | Disturbance type | Comments |
|                                 |                 | No              | No              | Smooth | The proposed technique is just designed for tackling the unmodelled factors and disturbances in general and no specific discussion is made regarding payload, wind disturbance and rotor efficiency loss. |
The fuzzy set of rules are embedded with NIFMPC to address the constraints of control input but due to this process time increases hence UAV cannot perform aggressive manoeuvres.

Paper focuses on hybrid observers because this is one of the ways to address the issue of unmodelled dynamic factors. Researchers provided several methods where they used disturbance and extended state observers-based control laws to cope up with the cable suspended payload smooth and non-smooth disturbances. One should study and evaluate the mathematics so that it can also work for unbounded variation with partially known information. Researchers also proposed B-spline artificial neural networks with online disturbance estimation for a quadrotor unmanned aerial vehicle where the linear extended state again estimates the external disturbances.

The Table 6 is formulated using the basic understanding of predictive control optimisation method with nonlinear disturbance observer technique as proposed in Wang et al. By amalgamating it with any robust or adaptive control design, the better performance can be obtained. The measured and hypothetic parameters are shown in Table 6.

In the above Table 6, it summarises the performances of current conventional algorithm with the hypothesis suggested by this review. In this table, the steady state error and overshoot percentage is computed using integral square error method as stated below:

\[ ISE = \int e^2 dt \]  

where is the error rate which can be used separately for computing the steady state error and overshoots. In additions to this, MATLAB also provides built-in commands to find or compute the integral square error.

**Conclusion**

This draft proposes the need of acquiring more realistic quadrotor model using Euler formulation technique either quaternion method with three lumped unmodelled dynamic factors such that wind disturbance, payload variation and rotor efficiency loss. Moreover, proposes a need of predictive algorithm-based observer design methods fused with robust control designs to compensate the compromising responses such that delays in rate of change of velocities, unnecessary high oscillations, sudden overshoots and large settling time to do aggressive manoeuvres.

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**ORCID iD**

Ghulam E Mustafa Abro https://orcid.org/0000-0003-1874-1889

**Supplemental material**

Supplemental material for this article is available online.

**References**

1. Hoffmann G, Huang H, Waslander S, et al. Quadrotor helicopter flight dynamics and control: theory and experiment. In: Proceedings of the AIAA guidance, navigation and control conference and exhibit, Hilton Head, SC, 20–23 August 2007, p.6461. Reston, VA: AIAA.
2. Emran BJ and Najjaran H. A review of quadrotor: an underactuated mechanical system. Annu Rev Control 2018; 46: 165–180.
3. Gentle JE. Matrix algebra: theory, computations, and applications in statistics. New York: Springer, 2007.
4. Puri A. A survey of unmanned aerial vehicles (UAV) for traffic surveillance. Tampa, FL: Department of computer science and engineering, University of South Florida, 2005, pp.1–29.
5. Zhang X, Li X, Wang K, et al. A survey of modelling and identification of quadrotor robot. Abstr Appl Anal 2014; 1–16.
6. Huang H, Hoffmann GM, Waslander SL, et al. Aerodynamics and control of autonomous quadrotor helicopters in aggressive manoeuvring. In: 2009 IEEE international conference on robotics and automation, Kobe, 12–17 May 2009, pp.3277–3282. New York: IEEE.
7. Hoffer NV, Coopmans C, Jensen AM, et al. A survey and categorization of small low-cost unmanned aerial vehicles. Abstr Appl Anal 2014; 1–16.
vehicle system identification. J Intell Robot Syst 2014; 74(1–2): 129–145.
8. Yuan W and Katupitiya J. A time-domain grey-box system identification procedure for scale model helicopters. In: Proceedings of the 2011 Australasian conference on robotics and automation, Melbourne, 7–9 December 2011.
9. Lei X and Du Y. A linear domain system identification for small unmanned aerial rotorcraft based on adaptive genetic algorithm. J Bionic Eng 2010; 7(2): 142–149.
10. Chowdhary G and Jategaonkar R. Aerodynamic parameter estimation from flight data applying extended and unscented Kalman filter. Aerosp Sci Technol 2010; 14(2): 106–117.
11. Luo Y, Chao H, Di L, et al. Lateral directional fractional order (PI) α control of a small fixed-wing unmanned aerial vehicles: controller designs and flight tests. IET Control Theory Appl 2011; 5(18): 2156–2167.
12. Lima GV, de Souza RM, de Morais AS, et al. Stabilization and path tracking of a mini quadrotor helicopter: experimental results. IEEE Lat Am Trans 2019; 17(3): 485–492.
13. Yu X, Lv Z, Wu Y, et al. Neural network modeling and backstepping control for quadrotor. In: 2018 Chinese automation congress (CAC), Xi’an, 30 November–2 December 2018, pp.3649–3654. New York: IEEE.
14. Pazooki M and Mazinan AH. Hybrid fuzzy-based sliding-mode control approach, optimized by genetic algorithm for quadrotor unmanned aerial vehicles. Complex Intell Syst 2018; 4(2): 79–93.
15. Kayacan E and Maslim R. Type-2 fuzzy logic trajectory tracking control of quadrotor VTOL aircraft with elliptic membership functions. IEEE ASME Trans Mechatron 2016; 22(1): 339–348.
16. Liu H, Xi J and Zhong Y. Robust attitude stabilization for nonlinear quadrotor systems with uncertainties and delays. IEEE Trans Ind Electron 2017; 64(7): 5585–5594.
17. Ortiz JP, Minchala LI and Reinoso MJ. Nonlinear robust H-Infinity PID controller for the multivariable system quadrotor. IEEE Lat Am Trans 2016; 14(3): 1176–1183.
18. Dong W, Gu GY, Zha X, et al. High-performance trajectory tracking control of a quadrotor with disturbance observer. Sens Actuators A Phys 2018; 241: 67–77.
19. Bagheri A, Karimi T and Amanifard N. Tracking performance of a cable communicated underwater vehicle using adaptive neural network controllers. Appl Soft Comput 2010; 10(3): 908–918.
20. Dierks T and Jagannathan S. Output feedback control of a quadrotor UAV using neural networks. IEEE Trans Neural Netw 2009; 21(1): 50–66.
21. Santos M, Lopez V and Morata F. Intelligent fuzzy controller of a quadrotor. In: 2010 IEEE international conference on intelligent systems and knowledge engineering, Hangzhou, 15–16 November 2010, pp.141–146. New York: IEEE.
22. Yang H, Yu Y, Yuan Y, et al. Back-stepping control of two-link flexible manipulator based on an extended state observer. Adv Space Res 2015; 56(10): 2312–2322.
23. Wang K, Hua C, Chen J, et al. Dual-loop integral sliding mode control for robust trajectory tracking of a quadrotor. Int J Syst Sci 2020; 51(2): 203–216.
24. Derafa L, Benallegue A and Fridman L. Super twisting control algorithm for the attitude tracking of a four rotors UAV. J Franklin Inst 2012; 349(2): 685–699.
25. Venkataraman ST and Gulati S. Control of nonlinear systems using terminal sliding modes. ASME J Dyn Syst Meas Control 1993; 115(3): 554–560.
26. Fresk E and Nikolakopoulos G. Full quaternion-based attitude control for a quadrotor. In: 2013 European Control Conference (ECC), Zurich, 17–19 July 2013, pp.3864–3869. New York: IEEE.
27. Wang Y, Cai H, Zhang J, et al. Disturbance attenuation predictive optimal control for quad-rotor transporting unknown varying payload. IEEE Access 2020; 8: 44671–44686.
28. Cai W, She J, Wu M, et al. Quadrotor waypoint-tracking control under exogenous disturbances based on equivalent-input-disturbance approach. J Franklin Inst 2020; 357(8): 4709–4741.
29. Lu Q, Ren B and Parameswaran S. Uncertainty and disturbance estimator-based global trajectory tracking control for a quadrotor. IEEE ASME Trans Mechatron 2020; 25(3): 1519–1530.
30. Sharma M and Kar I. Nonlinear disturbance observer based geometric control of quadrotors. Asian J Control. Epub ahead of print March 2020. DOI: 10.1002/asjc.2318.
31. Flores G, González-Huitrón V and Rodríguez-Mata AE. Output feedback control for a quadrotor aircraft using an adaptive high gain observer. Int J Control Autom Syst 2020; 18: 1474–1486.
32. Xu B, Cheng Z, Zhang R, et al. PSO optimization of LADRC for the stabilization of a quad-rotor. In: 2020 12th international conference on measuring technology and mechatronics automation (ICMTMA), Phuket, 28–29 February 2020, pp.437–441. New York: IEEE.
33. Sanwale J, Trivedi P, Kothari M, et al. Quaternion-based position control of a quadrotor unmanned aerial vehicle using robust nonlinear third-order sliding mode control with disturbance cancellation. Proc IMechE, Part G: J Aerospace Engineering 2020; 234(4): 997–1013.
34. Chih-Liang H, Lai JY and Lin ZS. Sensor-fused fuzzy variable structure incremental control for partially known nonlinear dynamic systems and application to an outdoor quadrotor. IEEE ASME Trans Mechatron 2020; 25(2): 716–727.
35. Escobedo-Alva JO, Garcia-Estrada EC, Páramo-Carranza LA, et al. Theoretical application of a hybrid observer on altitude tracking of quadrotor losing GPS signal. IEEE Access 2018; 6: 76900–76908.
36. L’afflitto A, Anderson RB and Mohammadi K. An introduction to nonlinear robust control for unmanned quadrotor aircraft: how to design control algorithms for quadrotors using sliding mode control and adaptive control techniques [focus on education]. IEEE Control Syst Mag N Y 2018; 38(3): 102–121.
37. de Jesus Rubio J, Zamudio Z, Campana JA, et al. Experimental vision regulation of a quadrotor. IEEE Lat Am Trans 2015; 13(8): 2514–2523.
38. Xu Q, Wang Z and Li Y. Fuzzy adaptive nonlinear information fusion model predictive attitude control of unmanned rotorcrafts. Aerosp Sci Technol 2020; 98: 105686.
39. Guo K, Jia J, Yu X, et al. Multiple observers based anti-disturbance control for a quadrotor UAV against payload and wind disturbances. Contr Eng Pract 2020; 102: 104560.
40. Zhu B, Chen M and Li T. Robust constrained trajectory tracking control for quadrotor unmanned aerial vehicle based on disturbance observers. *J Dyn Syst Meas Control* 2020; 142(11): 1–10.

41. Miladi N, Dimassi H, Said SH, et al. Explicit nonlinear model predictive control tracking control based on a sliding mode observer for a quadrotor subject to disturbances. *Trans Inst Meas Contr* 2020; 42(2): 214–227.

42. Zhang B, Sun X, Liu S, et al. Tracking control of multiple unmanned aerial vehicles incorporating disturbance observer and model predictive approach. *Trans Inst Meas Contr* 2020; 42(5): 951–964.