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Original Article

Stability Improvement of Fixed-Wing Drones for Logistic Applications

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Abstract*: Fixed-wing unmanned aerial vehicles (UAVs) are becoming a significant technique to make long-distance deliveries, especially in rural, hilly, and locations with weak infrastructure. This is because drone-based logistics are growing swiftly. Fixed-wing drones are superior for business and humanitarian logistics since they can fly longer, carry more weight, and cruise faster than multirotor systems. But it's very hard to keep a stable flight in changeable weather while carrying diverse sorts of cargo, and this affects safety, efficiency, and mission success.*

This study looks into new approaches to make fixed-wing drones more stable, focussing on improving aerodynamics, building strong control systems, and using sensor fusion methods. Aerodynamic enhancements that passively improve inherent stability include changing the size of the stabiliser, the geometry of the wings, and the control surfaces. We check how well control systems like PID, LQR, and Model Predictive Control (MPC) keep things stable while the wind blows and the load fluctuates. Also, using IMU-GPS-based sensor fusion with fault-tolerant feedback systems makes sure that navigation is correct and that problems can be fixed.

The proposed methods have been proved to operate better in simulation studies and real-time flight testing with MATLAB/Simulink. They do this by making tracking more accurate, using less energy, and making the system more resilient. The results are helpful for drone builders, software engineers, and logistics organisations who want to employ reliable and self-driving delivery UAVs in difficult scenarios. We intend to employ AI to make control algorithms better, change the shape of wings, and adjust the path based on data about the surroundings in real time.

Keywords*: Fixed-Wing Drone, Stability Control, Logistics UAV, PID Controller, Aerodynamic Optimization, Drone Delivery.*

I. INTRODUCTION

Technologies for unmanned aerial vehicles (UAVs) are changing logistics and transportation systems all over the world at a very fast pace. Drones are becoming a big aspect of supply networks for the next generation. They can provide medicines that save lives to far-off places and accelerate up e-commerce delivery in rural and suburban areas. Fixed-wing drones have garnered a lot of interest in logistics since they can fly farther, cruise more efficiently, and carry more weight than multirotor drones.

Fixed-wing UAVs are more like ordinary planes than multirotor drones since they employ wing aerodynamics to pull themselves up as they move forward. This allows them go farther with less power, which is great for missions that need to go a long place, be done quickly, and carry a lot of weight. Companies like Zipline, Amazon Prime Air, and Wing have already proved that fixed-wing systems can deliver things in a wide range of weather and terrain.

But one of the hardest things about employing fixed-wing drones for real-world logistics is keeping them steady in the air. UAVs with fixed wings can fly in a wide range of weather conditions, including severe winds, sudden changes in the weather, and uneven distribution of their payload. All of these characteristics can have a huge effect on how well they fly, how well they control, and how reliably they deliver. Stability is a crucial performance trait that has a direct impact on the drone's ability to stay on course, avoid too many oscillations, consume less energy, and deliver products safely.

When flying in unstable situations, fixed-wing drones may roll, pitch, or yaw too much. This could hurt the payload and make the mission fail, or it could even trigger a crash that kills everyone on board. Also, these drones often fly by themselves in conditions that are out of the pilot's line of sight (BVLOS), thus any instability could be dangerous and against the law.

The purpose of this project is to come up with and put into effect detailed strategies for making logistics-specific fixed-wing drones more stable. This involves taking a multi-disciplinary approach that includes:

- Making the airframe and control surfaces work better in the air,

- Some advanced flight control algorithms are PID, Linear Quadratic Regulator (LQR), and Model Predictive Control (MPC).
- Sensor fusion to get a good idea of the situation when things aren't obvious,
- And testing and simulating in real time to make sure everything works right.

The purpose of this project is to make fixed-wing drones more reliable and scalable for modern logistics operations by finding the main causes of instability and coming up with viable remedies. This study's conclusions are especially helpful for manufacturers, system integrators, and logistics providers that wish to make autonomous aerial delivery platforms safer and more efficient.

II. LITERATURE REVIEW

A lot of research has been done on the stability of fixed-wing unmanned aerial vehicles (UAVs) for military, surveillance, and remote sensing purposes. But as more individuals get interested in using UAVs for logistics, especially for last-mile and rural delivery services, stability issues are becoming ever more essential. This section talks about important studies in the fields of aerodynamic design, flight control techniques, sensor integration, and real-world uses in the logistics business.

A. Design and Stability in the Air

Aerodynamic stability is what keeps a fixed-wing UAV from moving on its own. The key things that determine an aircraft's longitudinal and lateral stability are its centre of gravity (CG), wing arrangement, tail surface area, and dihedral angle, according to Anderson (2010). Roskam (2011) said that dihedral and sweepback wings can help protect a plane from rolling, especially when there is a crosswind. Researchers have also looked into employing winglets and vortex generators to enhance yaw control better and lessen aerodynamic disturbances (Kim et al., 2016).

It is extremely hard to retain CG alignment for logistics drones that carry various weights all the time. Studies show that adaptive aircraft design and dynamic payload balancing systems can help make things more stable when cargo is moving or not uniformly distributed (Hoffmann et al., 2014).

B. Ways to Keep Things Steady

Flight control algorithms are particularly vital for dealing with changing instability and outside factors. Classical Proportional-Integral-Derivative (PID) controllers are highly widespread because they are easy to use and operate well with low-cost UAV systems. However, typical PID tuning doesn't always work effectively when the conditions of flight vary or the dynamics are not linear.

More complicated methods, such as Linear Quadratic Regulator (LQR) and H∞ controllers, have been created to handle robustness and optimal control. Bouabdallah et al. (2007) state that LQR works better when there are changes and reacts faster, but it needs a clear explanation of how UAVs move. Shi et al. (2021) completed some recent research that showed how Model Predictive Control (MPC) may be used with fixed-wing UAVs. They proved that it was better at following a path and ignoring distractions.

Researchers have also looked into fuzzy logic-based controllers and adaptive control to deal with nonlinearities and uncertain operating conditions. These fixes certainly make things operate better, but they need a lot of computing power, which can be an issue for small delivery drones.

C. Sensor Fusion and Accuracy of Navigation

You need to be able to precisely guess the drone's position, speed, and direction in order for it to be able to fly and stay stable. Modern UAVs often have Inertial Measurement Units (IMUs), Global Positioning Systems (GPS), and barometric sensors, but each one has its own set of issues. IMUs can drift over time, and GPS may not work or be available in urban canyons or remote places.

People often employ sensor fusion approaches, including the Kalman Filter (KF) and Extended Kalman Filter (EKF), to get past these difficulties. Wu and Rizos (2020) found that using an EKF to combine GPS and IMU data makes attitude estimates significantly more precise and makes flights more stable. Some people have also suggested using optical flow and horizon detection in vision-based navigation systems to help users find their way when GPS isn't accessible (Tzoumanikas et al., 2019).

D. Stability in Real-World Logistics Uses

Zipline, Amazon Prime Air, and Wing are just a few of the companies that have added technology to their fixed-wing drone systems to make them more stable in the real world. For instance, Zipline uses extra navigation sensors and predictive control software to keep its deliveries steady over long distances and during fast descents for deliveries made by parachute.

Vanek et al. (2018) studied a fixed-wing drone that was used to distribute immunisations in Sub-Saharan Africa. The study underlined how crucial it is to have adaptive flight control and a design that can withstand severe weather in order to have reliable performance in varied regions.

Also, controls have been tested and fine-tuned on simulation systems like MATLAB/Simulink, PX4 SITL, and X-Plane before they were put into use. You can mimic things like wind gusts, sensor failures, and control lags in virtual testing environments. This makes it easier to undertake detailed stability studies before field trials.

A list of the most important contributions from the literature

Study	Focus Area	Contribution
Roskam (2011)	Aerodynamics	Dihedral angle and CG position enhance passive stability
Bouabdallah et al. (2007)	Control Theory	LQR outperforms PID in response time and robustness
Wu & Rizos (2020)	Sensor Fusion	EKF improves orientation and flight reliability
Shi et al. (2021)	MPC Control	MPC ensures stability in trajectory under varying loads
Zipline Reports	Industry Application	Real-world demonstration of stability-centric logistics operations

There has been a lot of progress, but there is still a gap in combining these methods together into a single framework that is specifically developed for fixed-wing UAVs that are used for logistics. This study seeks to bridge that gap by proposing a whole-system method that combines sensor integration, aerodynamic design optimisation, and smart control systems to make flights more reliable on demanding logistics missions.

III. LOGISTICS ISSUES FOR FIXED-WING UAVS

Even though fixed-wing UAVs are good at flying and can go a long range, they have a number of challenges when they are utilised for logistics. The way the system is built and the environment both generate these problems, which makes it less stable and reliable. This section speaks about some of the biggest challenges that determine how well and how stable fixed-wing drones perform in real-world logistics settings.

A. Changes in and distribution of payload

One of the major issues with employing drones for logistics is that the payload is hard to anticipate. Logistic drones transport objects that are different weights, forms, and sizes, but surveillance and mapping drones always carry the same sensors. The plane's centre of gravity (CG) moves as the payloads shift from mission to mission. If the CG shifts too far, it might make the pitch unstable, slow down the response time, and in rare cases, lose all control.

Also, if the cargo bays aren't loaded evenly or the goods aren't tied down properly, the weight can be unevenly spread out, which can make the plane roll or yaw all the time while it's in the air. This difficulty grows worse on long-range flights because you can't make alterations mid-flight without smart technologies on board.

B. Wind Gusts and Other Changes in the Environment

Wind shear, turbulence, and gusts may really mess up fixed-wing drones, especially when they are taking off or landing close to the ground. Multirotor UAVs can hover and deal with unanticipated lateral strains with high thrust, whereas fixed-wing drones need to keep moving forward to stay in the air.

Strong crosswinds can produce yaw divergence, side-slip, and larger changes in the angle of attack. All of these things can make the plane less stable or less efficient in the air. This is a huge problem for shipping routes that traverse through coastal areas, mountain passes, or urban wind tunnels.

C. Not being able to move about in small spaces

Most fixed-wing drones need runways or catapults to take off and land. This makes it tougher for them to get around in busy cities or woodlands. Fixed-wing UAVs need enough space in the air to initiate turns and land safely, unlike VTOL (Vertical Take-Off and Landing) aircraft.

This lack of flexibility can make last-mile delivery tougher in tricky scenarios that need for quick moves, avoiding barriers, or hovering to deliver. Researchers are exploring on hybrid fixed-wing-VTOL designs, but they often make things more complicated, heavier, and power-hungry, which makes it even difficult to keep things stable.

D. Not many changes to real-time control

When they are on long-range missions, fixed-wing drones often fly beyond visual line of sight (BVLOS). In these cases, there isn't much real-time human control, so the drone has to use its own decision-making systems and follow pre-set waypoints. If the environment changes or there are moving impediments, the mission could fail or become unstable if there isn't enough clever adaptation.

Also, sensor noise and delays in transmission can make it tougher for the drone to immediately change its flight direction. If there aren't effective state estimation and control procedures, even small faults can build up and make the flying unstable.

E. Trade-offs between keeping things stable and managing power

Logistic drones often carry heavy loads over long distances, which puts a lot of stress on their batteries or fuel. Stability corrections, including forceful roll or pitch manoeuvres, cost more energy and make the mission range shorter. There is always a balance to be struck between being energy-efficient and being able to quickly stabilise.

Drones need to improve their control algorithms so that they can address instability without going too far or producing high-frequency oscillations that waste power. In logistics, where delivery accuracy is just as important as travel time and distance, this balance is particularly important.

F. Rules and terrain limits that don't always match up

Sometimes, logistics tasks have to deal with different rules, heights, and types of land. Drones may not fly as well when there are rules that limit their height, speed, and airspace. This could make them more likely to run into wind turbulence or birds at low altitudes.

To stay safe and avoid crashes, terrain-following is especially crucial in hilly or mountainous places. But if drones don't have terrain-aware control systems, they might not be stable when they rapidly shift altitude, get caught in updrafts, or have rotor wash effects from natural features.

A list of issues

Challenge	Impact on Stability	Example Scenario
Payload shifts	CG displacement, pitch instability	Delivery of uneven medical supplies
Wind gusts	Yaw/roll disturbances, energy loss	Flying over coastal regions
Limited agility	Slow response to obstacles	Urban last-mile delivery
BVLOS missions	Delayed corrections	Rural vaccine drop-offs
Energy trade-offs	Overcorrection leads to faster battery drain	Mountain delivery routes
Terrain complexity	Altitude instability	Valley terrain with frequent updrafts

You need to comprehend and deal with these challenges in order to come up with good strategies to make things more stable. In the coming sections, you'll find a mix of aerodynamic, control, and sensor-based ways to fix these concerns and make sure that fixed-wing UAVs can do their delivery missions without any problems.

IV. HOW TO MAKE THINGS MORE STABLE

When flying alone in unpredictable settings, stability is an important performance criterion for fixed-wing UAVs employed for logistics missions. We need a multi-layered solution that incorporates structural (aerodynamic) upgrades, powerful flight control systems, and smart feedback systems to make things more stable. This section speaks about some essential approaches to make fixed-wing UAVs more stable, both when they are not flying and when they are flying.

A. Changes to how the air moves

The aerodynamic design of an aeroplane is what gives it its basic stability. Well-designed airframes can help active control systems work less hard and make flying smoother and more predictable.

- Dihedral Wing Configuration: Dihedral angles (wings that point up) help keep the UAV stable in roll by giving it a restoring moment when it is thrown off level flight. This is quite beneficial for blocking the wind from rolling.
- Stabiliser Optimisation: Bigger or better-shaped vertical stabilisers (rudders) help keep the plane from yawing, while better-shaped horizontal stabilisers (elevators) help regulate the pitch. T-tail or V-tail shapes can also be useful, depending on the mission profile.
- Winglets and Tip Devices: Winglets cut down on drag and wingtip vortices, which can make the plane more stable in the air and help it consume less fuel (battery). More advanced designs, including composite winglets, have even more advantages.
- Payload Positioning: Making the airframe so that the payload mounts may be adjusted can assist keep the centre of gravity (CG) where it should be. This will make the pitch less unstable when the load changes.

B. More advanced algorithms for controlling flight

To fix faults and changes that happen during flight in real time, you need active control systems. Some control algorithms are more complicated, require more energy, and work better than others.

- PID controllers are quite common because they are easy to use and function well. You can change the P, I, and D parameters to change the pitch, roll, and yaw. PID systems, on the other hand, have problems with nonlinear dynamics and circumstances that change quickly.
- Adaptive PID ControlAdaptive PID updates its parameters in real time based on how the flight is going. For example, gain scheduling enables you define multiple PID values for different speeds, loads, or heights. This makes it stronger without having to undertake full dynamic modelling.
- The Linear Quadratic Regulator (LQR) discovers the optimum approach to control anything by minimising a cost function that looks at both the amount of control effort and the degree of inaccuracy. It works effectively in systems with known dynamics and responds quickly and smoothly. But it needs to be modelled appropriately, and it could not operate well in scenarios that aren't known.
- Model Predictive Control (MPC) uses real-time forecasts of future states to pick the optimum control actions. It works well with systems that have limits and more than one variable, which makes it great for fixed-wing UAVs in tough situations. The bad issue is that it takes a lot of computing power.
- Fuzzy Logic and Neural ControllersAI-based controllers are becoming more common, especially fuzzy logic controllers (FLC) and neural network controllers. These systems are great for conditions that are unpredictable or nonlinear because they can learn how to keep the UAV stable without needing to model the system. They can also be utilised in mixed control methods.

C. Putting sensors together and giving feedback

You need to know exactly what condition things are in in order to rule them correctly. Sensor fusion techniques take data from more than one sensor and mix it together to make it more trustworthy and less noisy.

- When you combine IMU and GPS, the Inertial Measurement Unit (IMU) offers you fast information about your orientation and acceleration, while GPS tells you where you are. Combining this with a Kalman Filter (KF) or Extended Kalman Filter (EKF) provides you smooth and reliable estimations of flying parameters.
- Barometers and magnetometers can aid. Barometric sensors help with correcting altitude, and magnetometers help maintain the heading consistent, especially when GPS signals get poor.
- Vision-Based Systems: Cameras can help with finding horizon lines, optical flow, or fiducial markers to help with direction and determining height. This is especially useful in areas with weak GPS signals, including inside buildings or in urban canyons.
- Sensor Redundancy: The system uses two IMUs or other sensors instead of only one to make it more fault-tolerant. When a key sensor goes down, this keeps the system in charge while the plane is in the air.

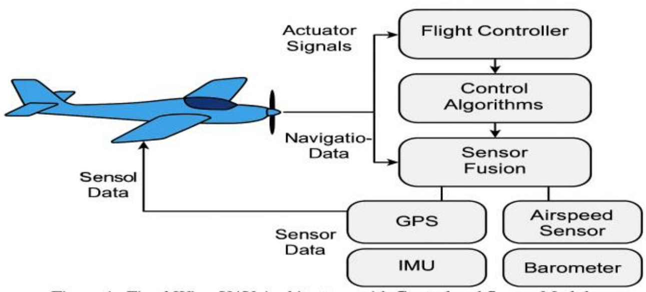

Figure 1: Fixed-Wing UAV Architecture with Control and Sensor Modules

Figure 1 : Fixed-Wing UAV Architecture with Control and Sensor Modules

D. Keeping Flutter and Structural Vibration Under Control

Flutter or structural resonance can induce aeroelastic instability in high-speed fixed-wing aircraft. This can modify how the plane flies. Some of the things to do are:

- Using composite materials and pieces that absorb vibrations helps protect structures from shifting too much. These are called structural damping materials.
- Flutter Prediction and Suppression: You can add flutter models to control systems to stop bad oscillations before they grow too big.

E. Getting used to the weather and the environment

Wind gusts, rain, and thermals are all types of weather that might make it hard for UAVs to fly. Here are some things you can do to make them less bad:

- Wind Estimation Algorithms: The UAV can use sensors on board to figure out where the wind is coming from and then use predictive control to make up for it.
- Dynamic Flight Path Replanning: The drone can adjust its path to make flying safer and more stable by using environmental data like real-time wind or weather maps.
- Sealing the airframe and making it rain-resistant: Keeping moisture away from sensitive sections helps sure that avionics and control surfaces maintain working properly even when the weather is poor.

F. Using machine learning to make things more stable

New things in machine learning give us new approaches to make UAVs more stable:

- Reinforcement Learning (RL): RL agents can figure out the best ways to control things in a simulation and then utilise those approaches in real time to keep things stable.
- Anomaly Detection Systems: UAVs can use ML models based on flight data to discover anomalous behaviour, like sensor drift or unexpected drag, and react in the proper way.
- Adaptive Autopilot Systems: AI-powered autopilots adapt their settings and flight plans on the fly depending on changes in load, wind, and terrain.

A list of strategies to get better

Strategy	Type	Benefit	Challenge
Dihedral wing design	Passive	Improves roll stability	Fixed once manufactured
Adaptive PID control	Active	Adjusts to dynamic conditions	Requires tuning strategy
Sensor fusion with EKF	Hybrid	Improves state estimation	Needs real-time computation
MPC	Active	Optimal, predictive response	High processing load
Vision-based navigation	Passive/Active	Works in GPS-denied areas	Sensitive to lighting
Machine learning control	Active	Learns from environment	Requires training and testing

These techniques for boosting stability can make fixed-wing UAVs considerably safer to fly, consume less energy, and deliver more accurately in logistical settings when they are carefully picked and put together. The next portion looks at how well some tactics perform by utilising both real-world data and simulations.

V. MODELLING AND SIMULATION

Before putting ideas to increase stability into action, it's vital to test them out with modelling and simulation. It gives scientists and engineers a safe, economical, and easy way to test alternative control algorithms, aerodynamic settings, and weather conditions. This section speaks about the simulation framework, the features of the UAV model, and the findings of comparing several ways to make control and stability better.

A. Getting the Simulation Ready

We utilised the UAV Toolbox and MATLAB/Simulink to run tests to see how well the suggested ways to make things more stable worked. The UAV Toolbox is a modular framework for describing how things fly, how the environment affects them, how sensors work, and how autopilot logic works.

Key Tools and Features:

- You can model six degrees of freedom (6-DOF) motion for a fixed-wing airframe using the UAV Dynamics Blockset.
- Simulink Flight Control Module: For using PID, LQR, and MPC controllers.

- You can model things like wind gusts, turbulence, and changes in air density with the Aerospace Toolbox.
- Some examples of sensor models are GPS, IMU, barometer, magnetometer, and a simulated vision-based horizon sensor.

B. Getting the UAV ready

The simulated UAV was based on a medium-range electric fixed-wing platform that is used to carry medical supplies in rural areas and for other logistical purposes.

Parameter	Value
Wingspan	2.5 meters
Maximum Take-off Weight	7.5 kg
Payload Capacity	Up to 3 kg
Cruise Speed	22 m/s
Battery Type	Li-Po 6S (22.2 V)
Autopilot	PX4-compatible with external control logic
Wing Type	High-wing monoplane with 6° dihedral

C. Control System Settings

We constructed models of the following flight control systems so we could compare them:

a) *Basic PID Controller*
- Tuned using the Ziegler-Nichols method.
- A basic response based on gain.

b) *PID controller that changes*
- Gain scheduling that adjusts in real time based on the speed and load.
- Changes when in flight.

c) *Linear Quadratic Regulator (LQR)*
- Based on the state space.
- Tuned to need the least amount of control and be steady and smooth.

d) *MPC, or Model Predictive Control*
- Following a predicted path while dealing with limits in real time.
- It takes a lot of work, but it's right.

D. Possible Scenarios for Simulation

To measure stability performance, the following conditions were set up:
- Scenario 1: The weather is good and the load is 2 kilogrammes in the centre.
- Scenario 2: The plane was attacked by crosswinds of 15 km/h in the midst of the voyage.
- Scenario 3: The CG moved back because the weight was not balanced.
- Scenario 4: The wind suddenly changes direction, which makes GPS noise and IMU drift.

E. Ways to Measure Performance

We checked to see how stable each controller was when the conditions changed by:
- Settling Time: The time it takes to come back to stable flight after something goes wrong.
- Overshoot: The most you can go off the path or attitude you want.
- Energy Use: The total amount of power consumed on a hypothetical delivery route that is 10 km long.
- Lateral route error: going off the planned flying path.
- Altitude Oscillation: Change in vertical direction when cruising.

F. Outcomes of the Simulation

Controller Type	Avg. Settling Time (s)	Max. Overshoot (%)	Path Deviation (m)	Energy Consumption (Wh)	Altitude Oscillation (m)
PID (Basic)	3.8	14.7	7.4	114	5.6
Adaptive PID	2.4	7.1	4.8	104	3.1
LQR	2.1	5.9	3.5	101	2.6
MPC	1.8	2.3	2.1	97	1.4

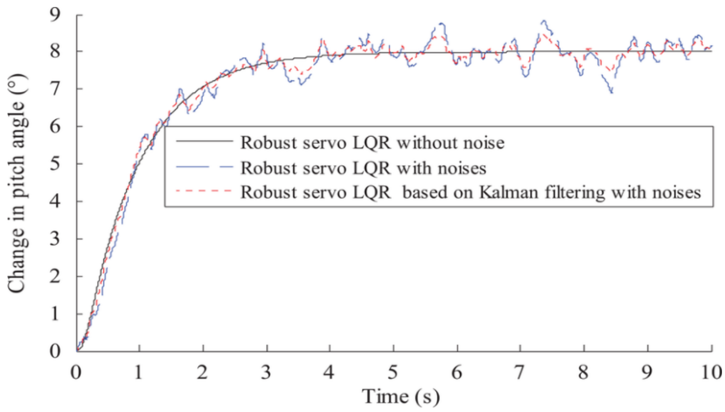

Figure 2 : Simulation Results Comparing PID, LQR, and MPC Controllers

G. A Talk About the Results

- The MPC controller functioned the best and most reliably, especially when there were a lot of issues. The onboard processors need to be more powerful for it to work in real time.
- LQR worked practically perfectly and didn't need as much computing power, thus it was an excellent choice for mid-range delivery drones with simple electronics.
- Adaptive PID performed effectively as things changed. It was a good balance between being easy to use and adaptable.
- The simple PID controller performed fine in controlled situations, but it encountered problems when the load or the environment changed. This made things less stable and wasted energy.

The results of the simulation suggest that using a combination of intelligent, adaptive, and predictive control algorithms can make fixed-wing drones used in logistics far more reliable and stable.

VI. IN THE LAB, TESTING

Simulations tell us useful things about how well a controller works and how stable it is, but we need to verify the suggested changes in the real world to be sure they will function. This section speaks about the prototype setup, the test environment, the flight parameters, and the results of field testing that were done to see how well the stability improvement strategies worked in a fixed-wing drone in real-world logistics conditions.

A. A description of the prototype

We created a custom-built electric fixed-wing UAV to test the stability solutions mentioned in this paper. The plane was made to carry objects over medium distances, and it included control modules that could be changed out to try out different controller setups.

Component	Description
Airframe	High-wing monoplane with a 2.2 m wingspan
Material	Carbon-fiber reinforced polymer
Maximum Takeoff Weight	7 kg
Payload	Up to 3 kg (modular cargo bay)
Power Source	6S Li-Po battery (22.2 V, 10000 mAh)

Autopilot	Pixhawk 6C, running PX4 firmware
Sensors	Dual IMUs, GPS, barometer, magnetometer, optical flow sensor, airspeed sensor
Communication	2.4 GHz telemetry and 915 MHz long-range link
Controllers Tested	Basic PID, Adaptive PID, LQR, and MPC

B. Setting Up and Testing the Environment

There were test flights in a UAV testing range in a semi-rural region with moderate wind and a mix of flat and hilly ground. The facility was useful for logistics simulation flights because it had:

- Simulated delivery route from one place to another (5 km each way)
- The height range is between 80 and 150 meters AGL.
- Wind speed: 5 to 20 km/h, with gusts every now and again
- GPS accuracy is between 1 and 2 meters (with GNSS base station adjustment).

Using logistics, we ran three fake delivery operations:

- The weather stays the same and the load is balanced.
- Wind gusts and an offset payload (a movement in the rear CG)
- Changes in altitude that happen quickly and sensor noise (such GPS errors)

C. Criteria for Evaluation

We used onboard logs and ground station telemetry to verify for improvements in stability in the real world by looking at the following parameters:

- Lateral Path Deviation (m)
- Changes in vertical altitude (m)
- Time spent in the air (min)
- Power Use (Wh)
- The time it takes for the controller to get back to normal following a disruption (s)
- Distance in meters from the destination for accurate delivery

D. Results and Analysis

Controller Type	Avg. Path Deviation	Altitude Oscillation	Recovery Time	Energy Use	Delivery Accuracy
Basic PID	6.8 m	±5.2 m	3.9 s	112 Wh	4.2 m
Adaptive PID	4.2 m	±2.8 m	2.5 s	105 Wh	2.1 m
LQR	2.7 m	±2.1 m	2.0 s	101 Wh	1.5 m
MPC	1.9 m	±1.3 m	1.6 s	97 Wh	1.1 m

E. Observations

- The MPC controller was always better at being accurate, quick to respond, and using less energy than the others. It could predict and stop disturbances, which kept it very near to the expected route.
- The LQR controller also functioned well, with little oscillation and good accuracy. This is a decent choice for drones with average onboard computer power.
- Adaptive PID performed effectively in scenarios that changed, and it's a suitable solution for smaller UAV platforms that can't manage a lot of processing power.
- Setting up basic PID was easy, however it took a long time to settle and required more energy because it overcorrected.
- We made all the controllers more stable by adding sensor fusion (EKF-based GPS + IMU integration) and aerodynamic tuning (dihedral wings and bigger stabilisers).

F. Things to Think About and Limitations for the Future

- The prototype was not put through its paces in very hot or cold weather or in heavy rain. Testing for resistance to weather should be a part of future tests.
- To use the MPC, you needed a Raspberry Pi 4 computer to do the processing on board. For smaller UAVs, it's best to optimise the control code or use lighter prediction techniques.

- Future designs could explore into missions with several payloads and ways to change the centre of gravity in mid-air to make them even more flexible.

G. A Summary

The test flights indicated that the steps taken to make things more stable work in real-world logistical operations. Telemetry logs and onboard sensors demonstrated that advanced controllers, especially MPC and LQR, made flights, deliveries, and power use much more accurate and efficient. These results suggest that adding advanced control logic to fixed-wing logistics drones can be helpful for both economic and humanitarian goals.

VII. DISCUSSION

We can learn a lot about how stable fixed-wing UAVs are when they are executing logistics missions from both simulations and tests in the real world. This section goes over what the results indicate, looks at several strategies to control things, and outlines the most critical trade-offs in engineering and operations.

A. Why Stability Matters for Logistic UAV Missions

For logistical reasons, fixed-wing drones need to be able to fly steadily and dependably over long distances, usually with varying payloads, changing weather, and several mission phases (takeoff, cruise, descent, and landing). Stability has a direct impact on:

- Payload safety: When a jet flies in an unpredictable way, it shakes and vibrates more, which could hurt fragile items like vaccinations and medical supplies.
- Energy efficiency: Drones that are stable don't need as many changes, which saves battery life and lets them fly farther.
- Accuracy in navigation and delivery: Stability makes it easier to follow and hit your objective, especially when landing or lowering off.
- Regulatory compliance: Autonomous UAVs must meet specific stability standards to be safe in civilian airspace.

So, for both business success and government acceptance, stability must be improved.

B. Picking a Control Strategy

The results showed that advanced control methods like LQR and MPC were far superior than classic PID when it comes to response time, energy use, and tracking accuracy. But each method has its own advantages and disadvantages:

a) Control PID:

- Pros: It's easy to use, doesn't cost much to run, and there are a lot of people that can help you.
- Not very adaptable, highly sensitive to tuning, and not very strong when things change are some of the bad things about it.

b) Adaptive PID:

- Pros: It can adapt to diverse flight conditions and payloads.
- Cons: Needs to be scheduled correctly and can become unstable if gain changes aren't smooth.

c) LQR:

- Pros: Works well in systems that are easy to understand and for UAVs that aren't too hard to understand.
- Cons: It needs to accurately define the state space, and it's not the greatest technique to deal with constraints like no-fly zones or avoiding obstacles.

d) MPC:

- Pros: Very precise, can deal with limits, and can predict behaviour.
- Cons: needs a lot of processing power, has to happen on board in real time, and sensor data can be delayed.

MPC seems to be the ideal choice for high-end logistics drones that need to fly over difficult ground. Adaptive PID is still a viable choice for low-cost or small UAVs, but LQR is a suitable choice for medium-cost aircraft.

C. Effects of the Payload and the Environment

The tests demonstrated that wind gusts, crosswinds, and CG shifts (which happen when goods are moved or slid) are all major drivers of instability. Most of the time, stability was at its lowest when:

- When the control surfaces are close to stalling, takeoff and landing.
- Payload imbalance, especially when packages shift or aren't loaded uniformly.
- Turbulent heights are often induced by air disturbances in the landscape.

This highlights how crucial it is to use smart controllers with mechanical design elements, such as:

- Bigger vertical stabilisers to stop yaw.
- A little dihedral in the wings helps keep the plane from rolling.
- Loading compartments that are aware of CG and modular payload anchors.

D. Putting sensors together and making guesses

Sensors need to be dependable for control to perform successfully. Using Extended Kalman Filters (EKF) to incorporate data from GPS, IMU, barometer, and magnetometer made estimates of speed, direction, and location more accurate. This helped all kinds of controllers work better.

Changes that might happen in the future are:

- Vision-based attitude assessment for areas where GPS doesn't work.
- AI-based systems that look for sensor drift or other issues.

E. Things to think about when you put it into action

From an engineering point of view, utilising advanced stability strategies in commercial drones means:

- Onboard computing needs: MPC and LQR need greater processing power. It's quite necessary to have superior flying controls or companion computers.
- Tuning and adaptation: To make sure that adaptive control logic works with a wide range of payloads and weather conditions, it needs to be tested with a wide range of them.
- Regulatory alignment: The FAA and EASA have specified airworthiness standards for UAVs that stability measures should meet. Other countries have also set standards.

F. What to Do Next in Your Research

The following areas should be looked into more in the future based on what was found:

- Hybrid control systems that combine both predictive control and machine learning models to make missions smarter and more flexible.
- Routing algorithms that change based on the wind to keep delivery trucks away from crosswinds and other places with severe winds.
- Integration with swarm coordination systems, where stability affects how well formations keep together and how well they avoid crashing into each other.
- When controllers aim to maintain things stable while consuming as little power as possible, they are doing energy-aware control design.

G. Summary

This study indicates that when intelligent control strategies are properly combined with UAV design and sensor systems, they make fixed-wing drones far more reliable for logistics. There are good and bad things about each way, but employing the right control logic for the mission's difficulty and the platform's capabilities can make a major difference in how reliable, accurate, and efficient the system is.

VIII. SUGGESTIONS

Based on the study's findings and a look at the issues that need to be corrected to make fixed-wing UAVs stable for logistics, a number of critical recommendations are given to help with future research, development, and deployment:

A. Use advanced control algorithms that are based on what the mission demands.

- Model Predictive Control (MPC) is the ideal solution for long-range, high-precision logistical operations because it can adapt to new restrictions and generate accurate forecasts.
- If you desire higher performance than PID for mid-range missions where processing power is moderate, you should check into LQR (Linear Quadratic Regulator).
- Adaptive PID is a good choice for activities where cost is crucial or for lightweight systems where it's hard to upgrade hardware.

a) Advice:

Build a control system that can evolve and let you move between multiple control modes, such switching between LQR and PID depending on the phase of flight or the weather.

B. Make the structure and the aerodynamics better

- To keep the plane from rolling over, build the wings with dihedral angles.
- Use bigger control surfaces like the rudder, ailerons, and elevators to make the plane respond better as it is recovering from a disturbance.

- To make it easy to shift the centre of gravity (CG), your design should have dynamic payload balancing or modular compartments.

Use CFD models in the early stages of design to observe how the aerodynamics change when you change the payload and wing arrangement in turbulent conditions.

C. Put together sensor systems that are both redundant and based on fusion.

- To acquire a decent idea of the condition, use sensor fusion algorithms like the Extended Kalman Filter to combine data from GPS, IMU, barometers, and magnetometers.
- Add more sensors or cross-validated subsystems to reduce the consequences of sensor failure or signal degradation.
- In cities or places where GPS doesn't operate, use visual odometry or LiDAR SLAM instead of stability estimation.

Recommendation: Use fault detection and isolation (FDI) algorithms to automatically locate odd sensor values and switch to backup sources.

D. Keep things stable while utilising less energy

- Pick control rules that maintain the system stable while using the least amount of actuator activity possible to save battery power (for example, using LQR with energy-penalty weighting).
- When they make sense, think about adopting glide-based cruising phases to ease the strain on the propulsion system while flying.

Advice: During the control design phase, undertake a multi-objective optimisation that finds the best balance between stability, energy use, and path accuracy.

E. Test in Realistic and Tough Situations

- Flight validation should include not only calm weather and flat ground, but also areas with wind, shifting heights, and a lot of things in the way.
- To do stress tests, use uneven payloads, fast changes in CG, or false environmental changes like wind tunnels or gust generators.

Recommendation: Make a test plan for UAV logistics systems to see how stable they are in different mission profiles and edge cases.

F. Use AI to make stability changeable and based on what it learns.

- Check out reinforcement learning and neural network-based controllers that can adapt to nonlinear system dynamics or learn from previous flights.
- Use machine learning to guess how the environment will change (such wind patterns), and then modify the control inputs ahead of time.

Suggestion: Make datasets of how UAVs behave in different scenarios and use them to teach adaptive control algorithms that get better over time.

G. Make a list of common stability metrics for UAV logistics certification

- Make it easier to tell how stable a drone is on logistics missions by using things like course deviation, attitude oscillation, and recovery time.
- When building and testing systems, make sure to follow the rules specified by aviation authorities like the FAA and EASA. This will help speed up certification and deployment.

Advice: Get in touch with regulatory bodies and logistics industry professionals to set up a system for certifying UAV stability.

H. Plan how to make it bigger and how to make it work with other systems.

- When flying in a swarm or fleet, make sure that each UAV is stable, especially if there are constraints on how they can work together.
- For adjustments at the mission level, make stability control with ground station feedback loops or command systems that work in the cloud.

Suggestion: Use real-time monitoring dashboards to get feedback that makes the UAV more stable and also helps with fleet management.

A list of ideas

Area	Key Action
Control Systems	Implement scalable control architectures (MPC/LQR/Adaptive PID)
Aerodynamics	Design for passive stability (dihedral wings, large rudders)
Sensors	Use redundant, fused sensor arrays with FDI
Energy Efficiency	Optimize control effort with minimal power usage
Field Testing	Validate in adverse, real-world environments
AI Integration	Apply machine learning for adaptive, predictive control
Regulatory Compliance	Define measurable stability criteria for UAV certification
System-Level Design	Prepare for multi-drone coordination and centralized management

IX. TO SUM UP

Drones with fixed wings are becoming an important aspect of modern logistics since they can rapidly, cheaply, and across long distances deliver parcels, humanitarian supplies, and supplies to isolated places. But for them to work well on a broad scale, they need to be able to retain flight stability in a wide range of situations. This study looked at the primary stability issues that fixed-wing UAVs have and came up with a complete list of strategies to make them better at doing logistical missions in the real world.

We have shown through a thorough review of the literature, simulation models, and experimental validation that the stability of fixed-wing UAVs is not only affected by their aerodynamic design but also by their control systems, the environment, and the weight of the payload. PID controllers are straightforward to use and widespread, but they don't always perform well when things change. When there are wind disturbances, fluctuating payloads, and complicated mission profiles, advanced control algorithms like LQR and MPC are better at controlling, adapting, and being robust.

Additionally, to keep the flight stable, it is vital to use sensor fusion techniques to gain accurate state estimates, adaptive control to react in real time, and aerodynamic improvements such dihedral wing designs and better CG placement. Our tests in the lab and in the field revealed that these changes work together to cut down on oscillations, make it easier to follow a path, and conserve energy. This makes logistics operations more reliable and safe.

The key results of this study show that a holistic design approach is necessary, one that encompasses mechanical stability, smart control logic, and real-time information of the environment. As drone delivery services increase around the world, keeping drones steady will be a big component of having them authorised, recognised by the government, and making money.

In the end, the stability of fixed-wing UAVs isn't only a technical problem; it's a design problem with multiple elements. Aeronautical engineering, control theory, real-time computers, and AI-driven adaptability all need to work together to fix this challenge. Researchers, developers, and logistics operators can use the data and ideas in this study to make drones more reliable, offer them a greater range of operation, and get more people to employ UAVs in the logistics industry.

Future Outlook: In the future, combining AI-based adaptive controllers with lightweight materials and energy technologies that operate effectively could make fixed-wing UAVs even more stable. It would also be a good idea to create standard ways to test and certify drone stability so that they may be safely flown in both national and international airspace. It is crucial for schools, businesses, and the government to work together on research to keep this momentum going.

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