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Recent advances and challenges in controlling quadrotors with suspended loads

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Abstract Quadrotors have been utilized in a variety of applications where the payload needs to be transferred from one location to another, such as in mine detection, load delivery through hazardous environments, or locations that are inaccessible to ground vehicles. In these applications, the payload will be suspended underneath the vehicle and is subjected to large oscillations due to external disturbances or the acceleration of the vehicle itself. In this article, the most recent advancements in controlling the quadrotors vehicles with suspended loads are presented including control algorithms and techniques to implement these controllers. These techniques include the hardware and sensors besides the testing techniques for the developed control algorithms.

Contents

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1. Introduction

The demanding nature of civilian and military applications has drawn a lot of attention to autonomous vehicles in recent years. Moreover, flying vehicles are the only option for solving specific applications that cannot be handled by land or water. Furthermore, applications requiring hovering and vertical take-off, limit autonomous vehicle solutions to rotary flying vehicles such as helicopters and quadrotors.

The quadrotor vehicle has more advantages compared with the helicopter such that the presence of four rotors that allow for load distribution and enables the quadrotor to have smaller rotor diameters, and hence smaller vehicle size, as compared to the single rotor helicopter. Furthermore, the smaller rotors, store less kinetic energy per rotor and thus reduce the extent of damage in the event that the vehicle is involved in a crash. In addition to that, rotors can be protected by enclosing them within a frame.

In situations when traditional ground vehicles cannot or should not be utilized, unmanned quadrotors with the ability to handle suspended cargo carried by a cable can be employed. Such as tracking moving targets, photographing for surveillance, rescue operations for natural disaster areas, discovering mines or inspecting gas and oil pipelines that exist in remote or hazardous areas.

A quadrotor is made up of a frame and motors that provide the forces needed to lift and move the vehicle whereas the suspended load is attached to the quadrotor frame's center, as shown in Fig. 1.

The vehicle with a suspended load system can be treated as a multi-body dynamical system. The equations of motion of each body can be written separately and then modified by adding the interaction forces between them using the Newtonian approach [1] or the Euler-Lagrange equations [2]. The Pendulous motion of a suspended payload with a cable can limit the applicability by either slowing down the flying vehicle or can damage the load itself. Moreover, the pendulum oscillation may prevent an accurate alignment during the pickup and/or placement of the load. In reality, a violent suspended payload swing can cause an accident [3]. It is thus critical to limit the payload swing to improve safety and performance.

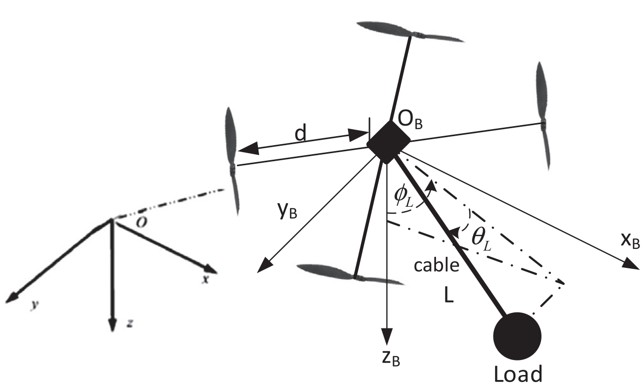

Fig. 1 Quadrotor with a suspended load.

In recent years, the delivery of packages has become an attractive application for multi-rotor vehicles, especially quadrotors. Many companies started offering this service such as Amazon [4]. The payload can either be rigidly attached to the quadrotor or suspended beneath the quadrotor by a cable. The rigid connection is the most common practice because of its practicality and simplicity. However, it is not suitable for heavy and large size packages and in some situations, it may not be possible to land the vehicle. Moreover, with this configuration, the inertia of the quadrotor will increase significantly which will reduce its maneuverability. With a suspended load, large packages can be carried with one or more quadrotors. This configuration allows delivering the package without the necessity to land the vehicle which improves the mission efficiency. However, it will complicate the dynamics and the performance of the quadrotor especially controlling the position of the payload in windy scenarios. Therefore, many researchers have recently begun to develop control systems for the quadrotor with suspended load to stabilize the vehicle and suppress the oscillations of the load besides accurate pickup and position of the load.

A quadrotor with no suspended load has fixed-pitch rotors and uses motor speed variation to control the vehicle, in this regard, attitude and altitude are the two most important variables to manage. Controlling a quadrotor, on the other hand, is difficult. This is due to the non-linearity of the quadrotor's dynamics and the uncertainties encountered during flight. Several control algorithms have been proposed in the literature. Among those controllers, are Proportional Integral Derivative (PID), Linear Quadratic Regulator/Gaussian-LQR/G, Sliding Mode Control (SMC), (Integrator) Back-stepping Control, Adaptive Control Algorithms, Robust Control Algorithms, Optimal Control Algorithms, Feedback Linearization, Intelligent Control (Fuzzy Logic and Artificial Neural Networks), and Hybrid Control Algorithms [5–11].

The abovementioned control methods and algorithms are applied in the case of a quadcopter without a suspended load. The suspended payload oscillation, on the other hand, must be kept under control and within particular limitations, and it must be damped.

In this paper, we present the most recent research work on developing and implementing control systems for quadrotors with suspended loads. The following is how the paper is structured: The developed control algorithms are presented in Section 2, and the hardware necessary to implement these controllers is described in Section 3. The strategies employed to put these control algorithms for the quadrotor with suspended weights to the test are discussed in Section 4, which is followed by the conclusion.

2. Control algorithms

The typical mission of the quadrotor with a suspended load can be divided into three regimes: takeoff, hover (or forward flight), and landing. In the following sections. Control systems developed for each regime are presented. There is a very little research work on takeoff and landing regimes, and most of the research appears to have focused on hover and forward motion flight regimes.

2.1. Takeoff

During takeoff, if the vehicle is moving vertically and the load is placed directly under it, the load will be raised vertically without oscillations. However, when the load is large and it is placed beside the vehicle at the beginning of the takeoff, the load will oscillate when the vehicle starts to move vertically. In such instances, a control algorithm is needed to reduce the load oscillations. Alothman et al. [12] investigated the takeoff maneuver and the performance of the quadrotor with LQR and PID controllers. In comparison to the PID controller, simulations revealed that the LQR has a better performance. In their papers [13–15]. Cruz et al. proposed a three-step procedure for the takeoff maneuver. The UAV rises vertically in the first step, then maneuvers to a position above the load while keeping the rope slack. The vehicle then rises vertically in the second step, with the cable fully extended. Finally, the vehicle begins to smoothly lift the payload into the air.

2.2. Landing

There is a lot of research work associated with the quadrotor landing mission [16–19]. However, only a few studies ~~works~~ have addressed the landing of the quadrotor with a suspended load. The classical approach for landing the payload is using a variable cable length by lowering the load through a mechanical mechanism while the vehicle is hovering above the desired location [20].

Graham presents an autonomous landing by recommending that the payload be lowered using the proportional navigation guiding law so that it lands softly. The proposed guidance law generates command inputs for the position controller which simplifies the implementation of this algorithm on the standard position controller of the quadrotor [13,21].

2.3. Forward motion

The suppression of the suspended load oscillation can be achieved by two general techniques:

1. Generate swing-free flight trajectories without the feedback of the payload states.
2. Adding an anti-swing controller to the vehicle by the feedback of the payload states which are the load swing angles.

These techniques are also utilized in different systems that have suspended loads such as gantry, tower, rotary cranes [22] and helicopters [23–26].

An accurate trajectory controller for the vehicle is necessary in the above-mentioned techniques. Designing a control system for an under-actuated mechanical system like a quadrotor has always been a difficult problem. In the case of quadrotor systems, the main focus of research has been on developing a viable trajectory tracking system and achieving quadrotor angle stabilization. Different control approaches have been developed in this regard in order to stabilize the quadrotor and apply proper tracking [5,7–9,27,28].

2.3.1. Flight trajectory approach

Das [29] applied the dynamic inversion control for directing the UAV to the desired coordinates and simultaneously minimizing the sway angle of the suspended mass. This study was conducted through simulations. Palunko et al. focus on generating a trajectory for the UAV that will minimize the payload swing during transportation along the path [30]. Kui et al. propose a sliding mode controller to track a given trajectory with the quadrotor using no explicit payload feedback, which worked well in simulation [31]. The quadcopter is assumed to be symmetrical, there is no damping force on the system, and certain constants are specified in this technique, which limits the generality of the problem solution.

During the cruising segment of the flight, it is possible to encounter disturbances due to wind or the swinging motion of the payload. Therefore, Nictora et al. proposed a controller that demonstrates some robustness to payload disturbances [32,33]. Qian and Liu present a path-following controller for the suspended payload system which is robust against wind disturbances on the system [33]. Guerrero et al. present a passivity-based approach to suppress the swinging motion of the suspended payload while tracking a trajectory [34,35]. Their approach was not dependent on the swing angle, and they found that the swing motion was suppressed along the flight trajectory. Some limits have been placed on the system in their approach, such as the cable being stiff and massless, the payload just to be a mass point, and the system being considered to be in the longitudinal plane. The proposed control method's validity is hampered by such assumptions.

Trachte et al. [36] described a System Dynamics and Control Simulation Toolbox for use with MATLAB/SIMULINK. Detailed simulation of the multirotor with slung load and the proposed predictive controller has been discussed. The main objective of this research is to manage the nonlinear dynamics but not neglect the system constraints. The controller (Nonlinear Model Predictive Control (NMPC)) has actually to track predetermined waypoints and in the meantime damps large slung load oscillations. The results show the importance of including wise trajectory planning to counteract cable forces resulting from heavy slung loads. As mentioned in the paper text, the introduction of NMPC is useful in avoiding problems arising from platform constraints. In addition, this controller decreases the overall control effort by employing predictive management on the actuating control elements. The authors also pay attention to the case in which power is limited. The method proposed in [34] cannot maintain a reference position under a persistent disturbance. This will lead to an avoidable constant load deflection.

An iterative linear quadratic regulator (iLQR) optimal controller is proposed by Alothman and Gu [37] to control a single quadrotor UAV with a cable-suspended heavy rigid body. The outputs from this controller are mainly to serve in achieving and precisely tracking a certain trajectory for a quadrotor with load and to avoid the load swinging during transport. The research has to guarantee the stability of the quadcopter carrying the load even in aggressive trajectory tracking. The authors formed a high nonlinear dynamic model of the quadrotor with the suspended load depending on Euler-Lagrange equations. The paper considers the loading effect only after taking off. Results obtained from the simulation have been discussed and compared with that case in which LQR is implemented. During the taking-off task, the method used examines a vehicle mode without a load effect.

In [38], the authors declare the research objective as swing-free transportation of the pendulum, while maintaining a precise trajectory. The controller used in this paper is a proportional derivative (PD) and a model predictive control (MPC). Not only a model of the quadrotor and the double pendulum has been constructed, but also experimental work has been reported in this article. The authors give their opinion on why they prefer to apply PD instead of applying PID. Such reasons are related to system constraints and the inclusion of Kalman filtering. The result section in the paper gives more numerical indices to prove that the MPC-PD is a better approach in controlling the pendulum swing angle. In this work aggressive maneuvers are not tested. Also, collisions of the payload with walls or payload taking off are not considered in the study.

A mixed H2/H∞ controller, based on linear matrix inequality (LMI) with constraints, is introduced in [39] in order to control a single quadcopter with a cable-suspended payload to follow the desired trajectory. The authors built a linearized dynamic model based on the Euler Lagrange. Their model is then extended to deal with the path tracking problem. Such modification in the controller allows the system to maintain a good balance in transient behaviors and frequency-domain performance. The action of the controller is seen in reducing the position error while the change in the quadcopter's attitude is still kept smooth as illustrated by the simulation results. The controller gives attention also to the swing angle in order to limit its aggressiveness. Constraints imposed on the system components, clearly, affect the system performance. For example, the quadcopter is considered to be a symmetrical rigid body and the payload is a point mass.

Sekiguchi et al. [40] apply the linearization method, known as hierarchical linearization, to the nonlinear under-actuated system of drone transportation of a cable-suspended load. According to the authors, the system can be linearized exactly and the controller can be designed simultaneously via the hierarchical linearization scheme. The system nonlinearity is considered by the controller, and the feedback controller is based on the linear control theory. The analytical solution of the closed-loop system is derived. Moreover, the singularity of the input transformation was evaluated. The singularity analysis provides valuable information for designing the reference trajectory. Numerical simulations verify the theoretical analysis. The load is suspended with a stiff cable with negligible weight, which is not the actual case.

Reinforcement learning (RL) has been used in several studies to overcome the challenge of trajectory tracking with a hanging payload [30,41–43]. In these investigations, the researchers employ RL to track and regulate the suspending payload's trajectory while striving to construct swing-free trajectories. The RL controllers show reduced payload swinging motion during agile dynamic movements along the target trajectory, demonstrating that this methodology works. However, this approach has the disadvantage of necessitating a significant number of flights to learn the control strategy. This can be minimized by utilizing a simulation to learn multiple iterations of flight methods. However, if flying tests are to be conducted, the simulation's dynamics must closely match those of the experimental platform. Despite these obstacles, the authors apply their findings to a prototype quadrotor and conduct successful flying testing in a motion capture facility.

Based on measurements from motion sensors installed on board, Outeiro [44] presents methodologies for height control of a quadrotor that transports a piecewise constant unknown load. Three possible solutions for controller design and state estimation have been discussed. The sub-optimal steady-state solution of a Linear Quadratic Regulator (LQR) is the core of the first controller. A Multi-Model Adaptive Controller, using LQR with integrative action, and Kalman filter with an integrative component is used in the second solution. An adaptive controller, scheduling LQR gains, and gravitational force compensation are the main items conducted in the last method. The Kalman filter was adjusted through a feedback loop with integration from the residue of the height sensor. An ordinary quadrotor, equipped with an Inertial Measurement Unit (IMU), an ultrasound height sensor, and a barometer, among other sensors, was used to perform the experimental work. Settling time not more than 7 s and overshoot of 4 % at most have been obtained from testing all controllers. All multi-model techniques were successful in selecting a model that was near to the real load and in identifying it adaptively. The authors propose to add horizontal position control for full position control. They also give attention to the control of a quadrotor with an unknown cable-suspended load and the control of a quadrotor for dropping a load while moving. The advantages and disadvantages of several feedback controllers have been summarized in [45]. The author also describes the dynamics of the quadrotor and quadrotor-with-payload systems. The idea of input shaping is dedicated to reducing the residual payload oscillations in the proposed model. MATLAB code is used for the simulations and for the verification of the design decisions of the quadrotor. The folding mechanism did not appear to incorporate any extra vibrational effects in experiments, implying that the current design is almost stiff in its behavior.

Guo and Leang [46] presented a new process for state estimation, trajectory planning, and dynamic control using a single onboard camera and inertia measurement unit (IMU). Thus, position estimation is not required. A least-square identification technique is employed to estimate the mass of each payload, and the input shaping technique is implemented to reduce the swinging motion of the payload.

Liang et al. [47] provide a nonlinear control approach with an elaborately constructed integral term for aerial transportation systems, which not only achieves satisfactory anti- swing and positioning performance but also reduces steady errors in practical flight. Meanwhile, the actuating constraint is taken into consideration to avoid saturation problems.

Lee and Son [48] proposed a method to generate a trajectory to minimize the swing motion and provide a dynamically feasible trajectory between waypoints. The proposed method provides a fast settling time with remarkably little payload swing. The performance of the proposed method is verified by numerical simulation and experimental results that show the possibility of safe and fast transportation with a minimal swing.

2.3.2. Anti-swing controller approach

The implementation of the time-delayed feedback concept to control the oscillation of the suspended load under the quadrotor was investigated through simulation by Sami et al [49]. The swing angles of the suspended load are measured and an additional trajectory is added to the original trajectory of the quadrotor based on the measured swing angles. This configuration was proven to reduce the oscillations of the suspended load. However, the designed controller was not validated practically on a quadcopter model.

Sadr et. al. [50] proposed an anti-swing control algorithm for the suspended load carried by a quadcopter. The dynamic model is derived using the Newton-Euler formulation. The Lagrange approach is employed to verify the model equations. This controller is nonlinear and is applied to control both the quadcopter's position and attitude. A forwarded control algorithm has been applied for damping the swinging load's oscillation in non-continuous and non-differentiable paths. The controller is designed based on the input shaping theory. Adding feed-forward control would improve the feedback control system response.

In [51], dynamics and control of a quadrotor with a payload suspended through an elastic cable have been introduced. The authors consider the cable to be elastic with both spring stiffness and damping. The system coordinate-free dynamic model is applied to include the effects of cable's elasticity. Singular perturbation is mentioned to limit the validity of the model to certain system parameter values. Numerical results are listed to validate the controller performance. Like the majority of authors, the work lacks experimental verification.

In [52], a simple active-model-based control scheme has been built for the quadrotor slung load system. Kalman filter (KF) is included to enhance the performance by rejecting the disturbances. Experimentally, the most popular controller Pixhawk is employed in the system field test. Results indicate the improvements gained by the inclusion of an active-model-based controller system. This is seen from the comparison of system operation with and without the proposed controller. In addition, the system is less in cost and can be feasible in commercial quadcopter applications.

Yi et. al. [52] considered a single multirotor carrying a suspended load. Dynamic modeling of the interconnected multirotor suspended load system is performed using Kane's equations. Based on this model, a nonlinear controller is designed, to guarantee trajectory tracking of the multirotor UAV while being subjected to disturbances from the motion of the suspended load. To minimize the swing of the load, an open-loop, and a closed-loop approach is considered and combined to achieve robust swing reduction. The proposed controller is verified by numerical simulations and experimental trials.

3. Controller implementation

3.1. Flight controller

The flight controller, which handles all of the tasks and controls that regulate the drone's flying, is critical to its efficiency and is one of the most crucial components in a quadrotor's operation. It is, in essence, the quadrotor's nervous system [53].

The applications of quadrotor UAV require a careful selection of hardware platforms in terms of size, weight, and power (SWaP) [54]. Another essential factor to consider when using UAVs is that they should be treated as safety-critical systems because their primary aim is to function in open-ended scenarios where living beings may be located [55]. Due to the demanding nature of the concerned problems of suspended payload in autonomous flight with quadrotor to a considerable extent, the research work has been published related to design an appropriate controller which can take care of not only the flight controls but also the parameters related to suspended load [2,15,29,33–36,38,41,56–92]. However, most of the researchers have validated their proposed controller with help of simulation work only, whereas very few examples are available in which researchers have used or developed a hardware platform to apply the designed controller. A Summary of the work is presented in Table 1.

In all the above-tabulated examples, in order to incorporate the swing angles of suspended load in the controller, motion capture systems are used which makes it necessary to depend on off-board processing which might be a drawback for autonomous flight operations with a suspended load.

The limited number of hardware implementations might be correlated with the fact that many UAV systems use proprietary closed-source flight controllers which makes this task more challenging: Exporting solutions for one controller to another may require extensive study and testing. It is possible to avoid some of these issues by using open-source flight controllers. This also allows other researchers to confirm and improve upon current studies. In general, open-source hardware platforms can be subdivided into four main types namely, FPGA-based, ARM-based, ATMEL-based, and Raspberry pi based. For the sake of a quick guide for the selection of an appropriate hardware platform, we offer in Table 2 [93–109] a list of the potential candidate for flight controllers with their characteristics (weight/frame size, type of processor, possible interface options, onboard available sensors, option to use in autonomous flight and available onboard memory).

For the successful hardware implementation of a controller for suspended load with a quadrotor, the selection of components for its construction must be chosen with the considerations of components accessibility and customization in mind. Furthermore, in order for the system to be sufficiently equipped for experimental purposes, it would be needed to include a way of transmitting and recording flight data. Based on the presented possibilities in Table 2, it is recommended by the authors that Pixhawk autopilot is considered for controller implementation since it is supported by both Matlab and Simulink software. In the Simulink environment, the controller may be created, and then uploaded to the pixhawk [110–114]. Monitoring and recording the system's performance may be

Table 1 Summary of hardware approaches to implement flight control with suspended payload.

Reference	Hardware implementation used in the reported reference
[14]	They used AscTec Hummingbird quadrotor to test their suggested approach. Flight control units (FCUs) [67–69] such as the AscTec Autopilot are installed on their aerial vehicle, in addition to linear acceleration sensors and gyroscopes that measure angular velocity. For autonomous control, they have utilized wireless serial link to receive attitude data. The position and attitude of the aerial vehicle and the load are determined via a millimeter-accurate motion capture system. To execute the control, Labview was utilized to provide a user interface on a Windows-based computer and a quadrotor interface that was be deployed by a National Instruments CompactRIO (cRIO) real-time controller [70]. Furthermore, the user interface software (UIS) acquires the quadrotor's pose data and the suspended load's position data and then employ the numeric differentiation technique described in [71] to estimate velocity and acceleration and generate the lift trajectory. In order to eliminate the high-frequency noise from the real data, a low-pass FIR filter of fifth-order is used. Attitude controller commands are calculated and sent to the quadrotor. A quadrotor's status is acquired and estimated by the UIS
[63]	These three components make up the hardware platform in this investigation. 1) A motion capture system (VICON) [72] that continuously updates information on the quadrotor's attitude and location, as well as the suspended load. The second is a desktop computer that receives location data from the VICON motion captions systems and, using a real-time algorithm in Matlab, evaluates the desired thrust and attitude by solving the optimization problem and sends it to the quadrotor every 0.02 s via the Zigbee module and the third one is Astec HymmingBird quadrotor equipped with a cable-suspended load and reflective markings for visual detection. Their UAV was outfitted with an Inertial and Measurement Unit (IMU) that provided information on the quadcopter's attitude data. Furthermore, its built-in controller allows the user to adjust the overall thrust, pitch, roll angle, angular coordinates of the pitch, and yaw angle's angular speed. A ZigB communication board helps to transmit control inputs to the aircraft and collect IMU data. The HummingBird can track an aggressive trajectory owing to the fast and high-precision 3D location data.
[73]	They utilized an Ascending Technologies Hummingbird quadrotor (having onboard IMU and Xbe module for communication) with an electromagnetically controlled load suspension system in this study. To give state information, a motion capture system (VICON) was employed. The load is considered as a point mass, and just the location of its center is monitored in this research, while the orientation is ignored.
[74]	Blade 200 QX [75], a unique mix of multi-axis sensors and software that allows the quadcopter to know its location relative to the horizon, was chosen as the UAV model for this investigation. A carbon fiber tube cable has been used to suspend the weight. Off-board, the flight control system was in use. Vicon vision data is used by a Matlab and Simulink program for Off-board the flight control system on a desktop computer, which processed the control algorithm in real-time and through an Xbee wireless connection sends the controller output to the quadrotor.
[73]	They built three quadrotor aerial robots using the F330 frame [76] and utilized the Optitrack motion capture system to identify their position in their research. There was a Pixfalcon flight controller board and PX4 autopilot software [77] installed on each quadcopter to manage the low-level control and do real time state estimations, respectively. Additional to this was the use of the ROS network and ODROID-XU4 [78] on each quadrotor for high-level trajectory tracking, which allowed it to communicate with the motion capture system.
[52]	This research employed a quadrotor with a Pixhawk flight controller and the original onboard PID algorithm [80,81]. They executed their suggested active estimation and augmentation control with the addition of an Odroid XU4 controller. The Qualisys motion capture system [82] measures the quadrotor's motion states at a sampling rate of 200 Hz.
[41]	The MARHES multi-aerial vehicle testbed was used for real-time tests. While the in-depth description of this testbed is given [83] along with its real-time controller.
[84]	They employed an Ascending Technologies Hummingbird quadrotor with a suspended rigid-body load to demonstrate the viability of their suggested technique of designing dynamic paths. No further detail about the sensors and swing angle measurement method has been mentioned in their study.
[85]	They built a FLICK frame system with two primary elements to test and assess their suggested controller architecture for this study: an onboard portion that utilizes low-level PID controllers and an off-board part that uses MATLAB/Simulink models to executes high-level controller algorithms [52]. The Vicon Mx-T40 Camera system was utilized in conjunction with reflecting spherical markers to monitor the object trajectory [86,36]. The VICON or an onboard downward-facing camera [87] collected pictures of the specified target item in their FLICK configuration to determine the suspended load location. The images were transmitted to the ground station, which processed them to produce a point feature model of the target. Whereas on the ground station, the suggested control actions have been implemented by the Simulink model.
[88]	They employed an off-the-shelf F330 frame [89] for their investigation. An on-board Odroid XU-4 runs Ubuntu 18.04 and ROS to execute the landing mission's guiding law and position controller. Exynos5422 Samsung CortexTM-A15 and CortexTM-A7 Octa core CPUs have been utilized to implement complex instructions and algorithms on the XU-4 single board computer. It is also used to establish communication with the ground station and Pixhawk. On the other hand Communication between Pixhawk and Odroid has been established using a serial connection cable to receive sensor measurements and state estimates from the Pixhawk, and to send position information and commands to the Pixhawk from the Odroid. The onboard Odroid (running main control) was used as master and the ground station (to record data and send high level commands) to be the slave. For additional safety, they have also used a traditional R/C transmitter and receiver on the quadcopter to arm the quadcopter (through the Pixhawk) and switch to OFFBOARD mode, where it could be controlled through the Odroid. The transmitter was also used in emergencies to disarm or kill the motors on the quadcopter. By using Monofilament fishing line a slung payload has been attached to the quadcopter. They have also used payload releasing mechanism with the help of servo connected to Pixhawk AUX1 port. The vision system has been used in this study as well to estimate the swing angles
[90]	In order to test their proposed control scheme, they have used a self-assembled GF360 quadrotor, and PIXHAWK [91,92] as the autopilot of the quadrotor. A vision-based system has been used to measure the position and estimate the swing angles.

Table 2 Comparison of Different Flight controller Platforms. (Abbreviations used in this table are; barometer(b), GPS (g), Magnetometer(m), LED (L), Pitot Tube sensor (p), Bluetooth(bl), Wifi (w), Gravity Sensor (gr), temperature (tem), accelerometer (ac), co-processor(Co-p), Compass (comp), pressure sensor (press), I2C (I), UART(U), CAN (c), SPI (S), ADC (a), PPM (pp), S-Bus (sb), DSM (ds), DAC (da), PWM (pw), Xbee (x), Aux (au), HDMI (H), and Camera Link (Cam)).

Platform Categories	Hardwar Boards	Weight (g)	~Frame Size	Processor	Interface	Built in Sensors	Operating System	Coding Environment	License	Autonomous	On board Memory	Flash Memory	Ref.
FPGA Based	Phenix Pro	64	74 × 56 × 18	Xilinx Zynq SoC	c, h, cam k, LVDS, BT 1120-PL	IMU, HUB, GPS	Linux	Closed Source	GPLv3	✓	125 MB		[93]
	OcPoC	70	63 × 92 × 20		pw, I, c, Ethernet, s, JTAG, u, OTG, CSI	IMU, GPS, B, Wifi		ArduPilot	BSD	✓	–		[94]
ARM Based	Pix-hawk	38	82 × 50 × 15.5	STM32F427	sb, ds, pp, I, u, c, s, a,	IMU, B, M	MacOS Linux, QuRT or NuttX	ArduPilot, PX4	BSD	✓	256 kB	2 MB	[95]
	mRo R15 PixRacer	11	36 × 36	STM32F427 VIT6 rev.3	I, u, c	IMU, B, M, comp		ArduPilot, PX4	CC BY 4.0	✓	256 kB	2 MB	[96]
ARM Based	Pixhawk 3 Pro	45	71 × 49 × 23	STM32F427	pp, sb	IMU, B, M		ArduPilot, PX4		✓	384 kB	2 MB	[97]
	Pixhawk Cube	36	229 × 152 × 102	STM32F427	I, u, c, s, a, pp, sb, ds	IMU, TBA		ArduPilot, PX4		✓	256 kB	2 MB	[98]
	PX4 FMUv5 Cube	45	71 × 49 × 23	STM32F427		IMU, B, M		ArduPilot, PX4		✓	512 kB	2 MB	[99]
	Paparazzi Chimera		89 × 60	STM32F767	da,a,au,I, c, pp, sb, u, s,	IMU, B, M,p, GPS			GPLv2	✓	512 kB	2 MB	[100]
	CC3D	5.7	36 × 36	STM32F405 RGT6 ARM Cortex-M4	I, u, pp, sb, ds	Gyro, ac,	Linux, Windows or macOS	Libre Piolt	GPLv3	✓	4 MB		[101]
	Atom	4	15 × 7	STM32F103	I, u, pp, sb, ds	IMU		Libre Piolt	GPLv3	✗	4 MB		
	Naze 32	5.3	36 × 36	STM32F103CBT6	I, u, pp, pw, sb	Gyro, Ac, b, m comp,		CleanFlight, Beta Flight	–	✗	16 MB		[102]
	Sparky 2.0	13.5	36 × 36	STM32F405ARM Cortex-M4	I, u, c, b, pp, ds, da, iRCVR, Flex	IMU, B, M, comp		TauLabs or OpenPilot	CC-BY-4.0	✗	61 MB	1 MB	[103]
	Beaglebone Blue	36	175 × 112 × 40		s, I, u	ac, comp, b gyro	Linux	ArduPilot, PX4		✓	512 MB	4 GB	[104]
	Hobbypower KK2.15	20	51 × 51 × 12	STM32 F4	c, da, I	B, M, ac, gyro.	On board LCD	TauLabs, Open Pilot	GPLv3	✗	66 kB		[105]
ATMEL Based	APM 2.8	30	120 × 80 × 10	ATmega 2560	u, I pp, a	IMU, B, m, ac	Linux, Windows or macOS	ArduPilot	GPLv3	✓	4 MB		[106]
	FlyMaple	15	50 × 50 × 12	STM32F103	u, I, pw	IMU, B, M, gyro		Maple IDE	GPLv3	✗			[107]
Raspberry Pi Based	Navio 2	23	55 × 65	Raspberry PI 3	a, sb, u,I, pp	IMU, B, GPS,cop	Linux	ArduPilot, PX4	BSD	✓	1 GB		[108]
	Erle-Brain 3 + PXFmini	115	95 × 70 × 23.8	Raspberry Pi	u, I, a, pp, P	IMU, B, M, gyro, com, prestem,gr	Linux	ARDUpilot	CC BY NC-SA	✓	1 GB		[109]

accomplished using the mission planning software [115–118] with telemetry.

3.2. Sensors

In recent years, precise quadrotor payload, suspended by a cable/sling, positioning with minimal swing has been explored and developed mainly simulations based. This was due to the inherent disadvantage of requiring an additional degree of freedom in the mathematical model to account for the load's swinging behavior. Furthermore, the payload oscillation has a negative impact on the quadrotor's stability. In reality, a violent suspended payload swing can cause an accident [3], so it's critical to limit the payload swing to improve safety and performance. In the literature, some solutions to the problem of conveying a suspended payload with UAVs have been offered. In this section, we'll go over various methods for calculating swing angles so that a closed-loop anti-swing control system can achieve superior trajectory control performance against parametric changes and unanticipated disturbances [119–122]. Two main approaches have been used in the literature, estimation/observation, and measurement, as shown in Fig. 2.

In this section, possible ways adopted in the literature or could be used to measure the swing angle for proper feedback for anti-sway operation using the direct measurement method will be presented with illustrative diagrams for connection. The methods used to measure the swing angle for the suspended payload could be further divided into two principal categories: contact and noncontact, as shown in Fig. 2. As a general rule, it is recommended to measure swing angle by the contact methods because they provide greater precision and accuracy than the non-contact methods, despite having some limitations. It should, however, be noted that non-contact methods have their own merits, which will be discussed in the following subsection.

3.2.1. Contact methods

The contact methods can be divided into two approaches. In the first approach, the swing angles can be measured by a mechanism attached to the rope that carries the suspended load. The possible choices are Potentiometer, rotary encoders, and joystick position sensors as shown in Fig. 3.

The swing angle measuring system with a potentiometer [123] has a basic form, is simple to install, and, most importantly, can be used to make real-time measurements using a simple signal conditioning unit. But due to its mechanical nature, it is vulnerable to environmental effects, and precision might be lost due to friction wear and tear with excesses use.

Encoders have progressed from simple incremental encoders to more complex and precise multi-turn absolute encoders over time. Similarly, technology (Optical, magnetic, and inductive technology) has evolved significantly and provides alterna-

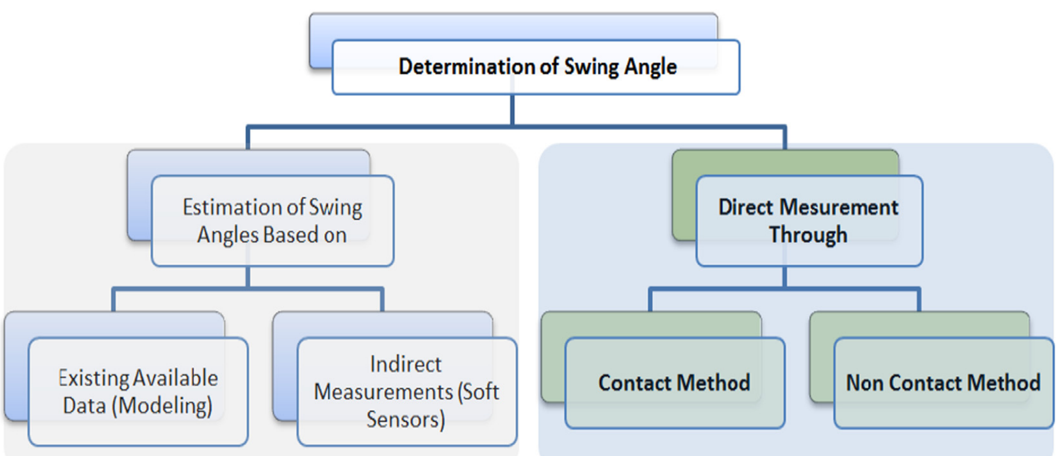

Fig. 2 Possible ways to measure the suspended payload swing angle for feedback control of quadrotor in anti-sway configuration.

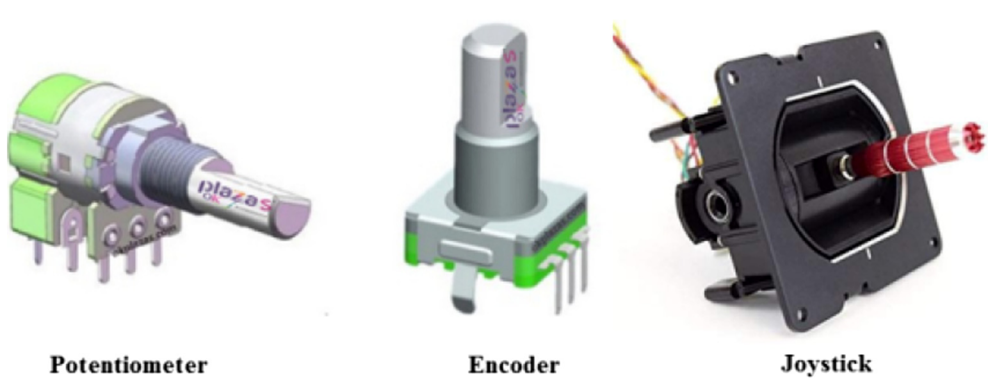

Fig. 3 Sensors that can be attached to the sling of the suspended load at the base of the quadcopter for swing angle measurement.

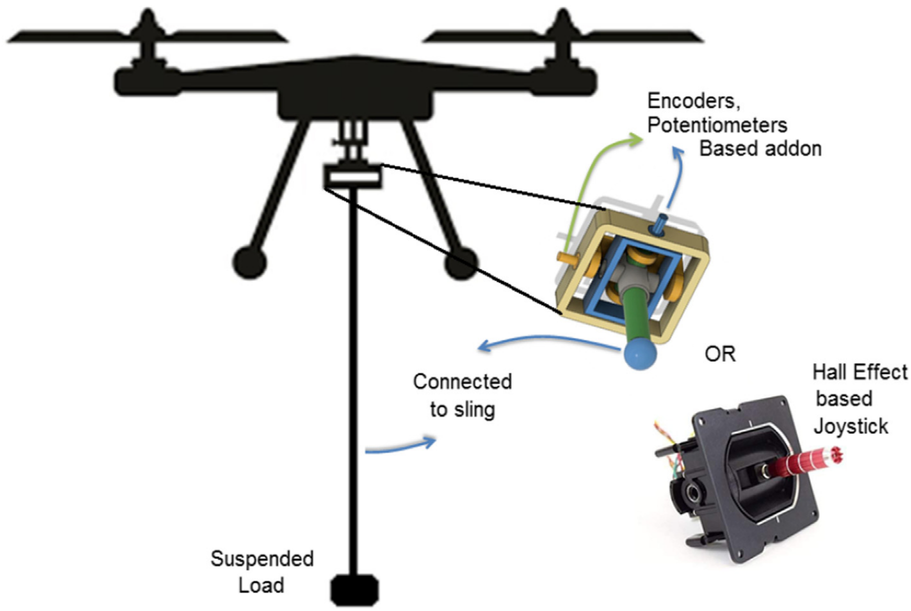

Fig. 4 swing angle measurement scheme using encoders, potentiometer, and joystick position sensor.

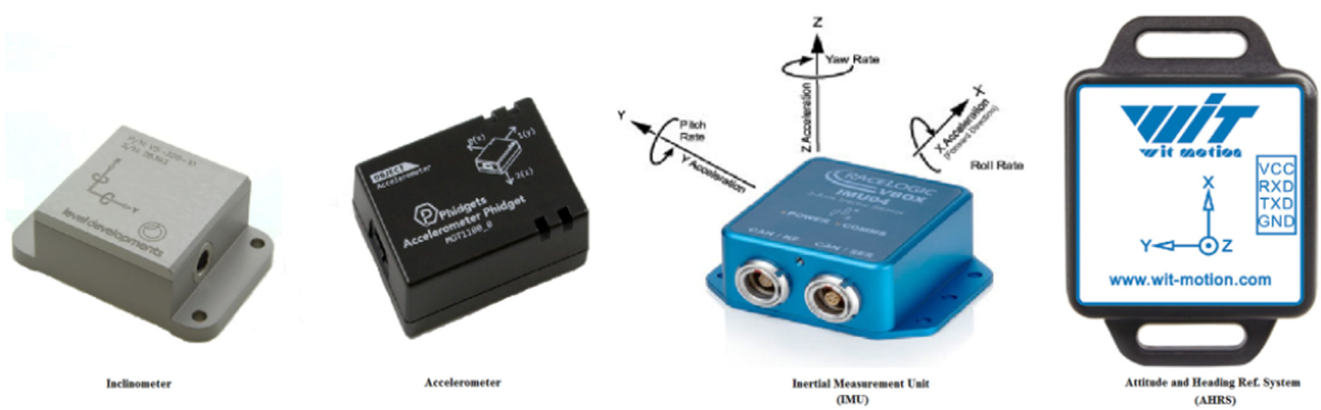

Fig. 5 Sensors that can be attached to sling of the suspended load at the base of the quadcopter for swing angle measurement.

tives, each with modest differences in measurement resolution and precision. The swing angle of the payload can be measured using rotary encoders [124–127]. The rotary encoder can also, simultaneously, measure the rotation angle [128] and the payload lifting height [127], (see Fig. 4).

The second approach is to add a sensor (Inclinometer, Accelerometer, Inertial Measurement Unit (IMU), and Attitude and Heading Reference System (AHRS) or a combination) to the suspended load and measure the tilt angle of the suspended load, as shown in Fig. 5 [129–131].

The technological development in the structure of inclinometer especially recent advancements in the field of MEMS technology such as Tiltix from Posital, made it possible to use it easily with sling suspended payload to measure the swing angles. Furthermore, with recent developments in the field of micro-electromechanical system (MEM) makes it possible to develop low-cost, small in size, and efficient inclinometers/accelerometers which are suitable for swing angle measurement, and a combination of all of these as Attitude and Heading reference system (AHRS) [132].

Swing angles can be easily computed by attaching these accelerometers/inclinometers to specific locations (base of quadcopter and at suspended load), depending on the geometry of suspended load. The main drawback is related to the situation when sling rotates, this can be overcome if orientation sensors are integrated as well. As illustrated in Fig. 6, the proposed swing angles measuring scheme employs two AHRS sensors. Where sensor 1 should be installed at the base of the quadcopter or near the control box and sensor 2 is mounted on the payload, both can be connected either through wireless communication or can be wired.

Though the accuracy of inclinometers, IMUs, and AHRs varies greatly depending on the type and technology used, in general, the accuracy of an inclinometer is higher than that of an IMU, and an IMU is better than an AHRS, while depending on the application, such as the one presented in this

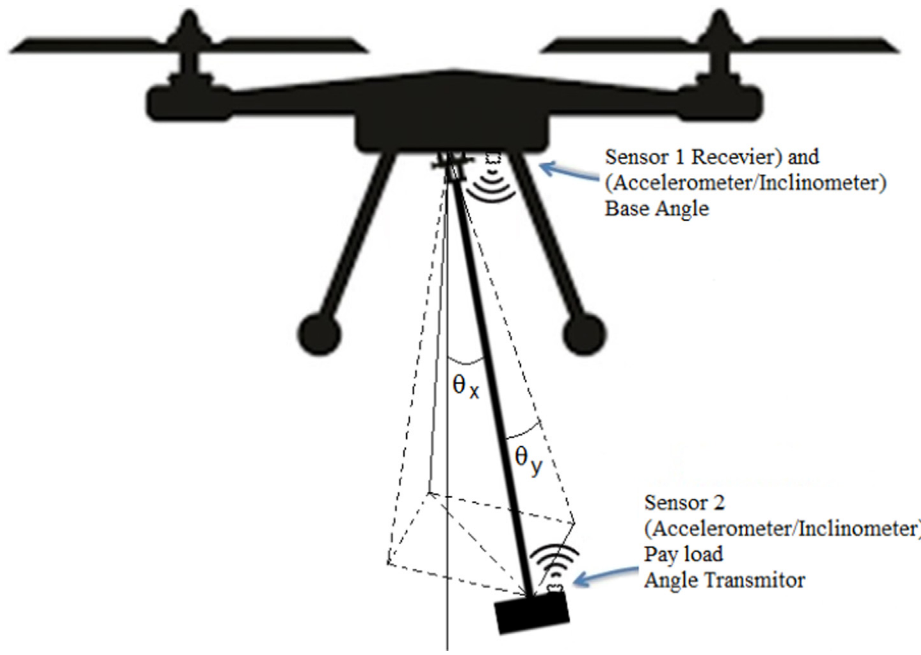

Fig. 6 Swing angle measurement scheme using accelerometer and inclinometer sensor either wireless or wired configuration.

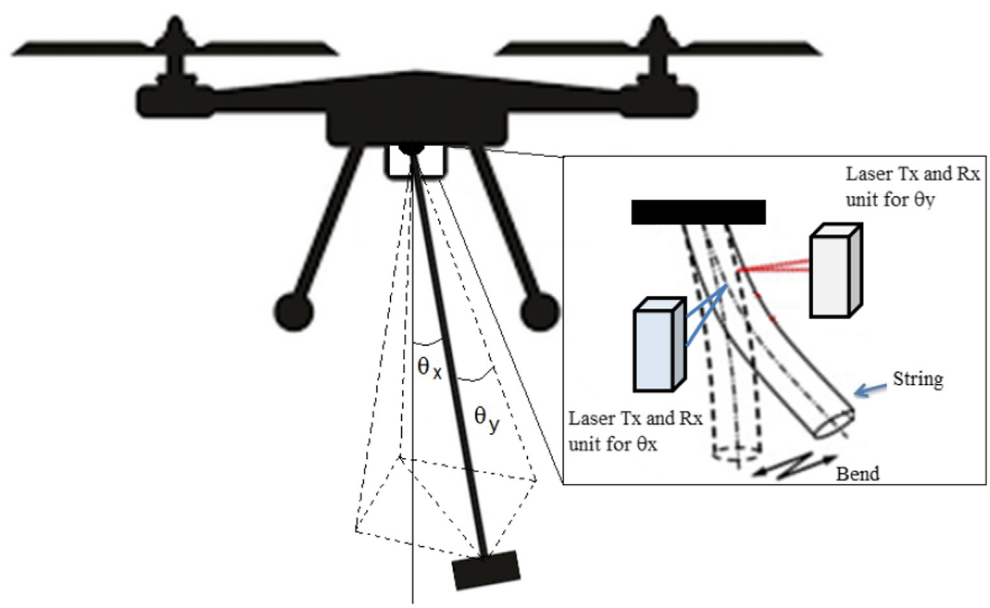

Fig. 7 swing angle measurement scheme using laser-guided sensing mechanism.

paper, AHRS and IMU, or a combination of these two, will be more feasible due to other advantages in terms of flight control. Furthermore, if wireless sensors are used then the measurement system's wireless capability allows it to be easily installed and is less affected by the weather conditions.

3.2.2. Non-contact methods

Non-contact methods are preferable as they don't affect the phenomenon under observation and have no loading effect but due to the nature of the setup and requirement of moving the target in this application, their application is quite limited. It is evident from the literature that they have been applied either for indoor applications or to check the validity of the developed controller design. Here we will present a few non-contact methods which are mainly applied for crane systems. Thereafter, we propose a modified system that can be applied to quadcopter for the calculation of the swing angle of the suspended load.

Laser Displacement Sensor (LDS): In a laser-based system, consisting of a sling fixed to a hosting and two LDS and reflecting plates, to determine the swing angle, the relative distance between the laser displacement sensor and reflecting surface is measured [128,133]. Following the same approach here we proposed a system for quadcopter with sling suspended load, which uses two laser displacement sensors which will be adjusted in hosting attached at the bottom of the quadcopter, and rope/sling will be coated with reflecting material to help in the reflection of the incident laser for detection purpose as shown in Fig. 7.

Camera Vision: Owing to the advantages related to non-contact measurement, Vision technology [134], has been widely used in industrial applications such as; assessing three-dimensional (3D) article placements [135], monitoring underwater robots [136,137], airplanes [138], and quantifying the size of objects [139]. Furthermore, the use of image sensing technology to measure swing angle for suspended load has steadily become a study focus for a growing number of scholars [140]. Three main machine vision methods which are used for automation and process control are monocular, binocular, and multi-camera vision methods.

The use of a Monocular vision-based detection system has been demonstrated successfully to detect swing angles of suspended load, the height of the payload, and its distance from the obstacles [141–144]. However, there are bottlenecks in this technique due to errors caused by background environmental noises (illumination, motion blur, etc.) [145], which need to be catered for by applying an appropriate developed signal processing algorithm [146–151] and this makes it heavy when integrated with the feedback onboard control loop to handle for processing during flight.

It is simple to produce 3D position information using Stereovision based on the binocular technique [152–154] and multi-camera vision measuring systems [155,156]. It has been demonstrated that the real-time position of the payload, swing angle, and other characteristics of interest can be measured using multi-camera vision systems with proper visual labeling on the load and rope. However, matching the features of two or more photos is frequently difficult for their image processing algorithms.

The system usually comprises of a camera attached at the bottom of the crane/quadcopter facing towards the suspended payload. The swing angle of the payload is calculated by applying the color histogram matching technique [157] and binary images [155,158,159] with the help of attached markers to the payload [160] or by applying vector code correlation [161,162] technique. This method necessitates the use of two cameras to determine the payload's swing angle, which is costly for the measurement system.

In general, vision-based noncontact swing angle measurement approaches using multi-sensors suffer from a variety of challenges, including a time-consuming process to calibrate the system for each flight and various environmental conditions, difficulty in synchronization of information acquired from multi-sensors, a complex system structure, and a high cost. On the other hand, regardless of the level of complexity of vision-based systems, a camera vision measurement system's accuracy can outperform LDS with an appropriate selection of pixels and vision processing techniques.

To reduce the cost of the entire system and make it more simple and practical, the proposed approach is shown in Fig. 8. It is a modified version of the system based on the smart camera- laser line emitter approach as described in [163]. In this method, housing will be attached at the bottom of the quadcopter which will include a camera and laser. The laser line makes the object plane where the camera records the swing of the rope by recording the laser marker on it, in the image

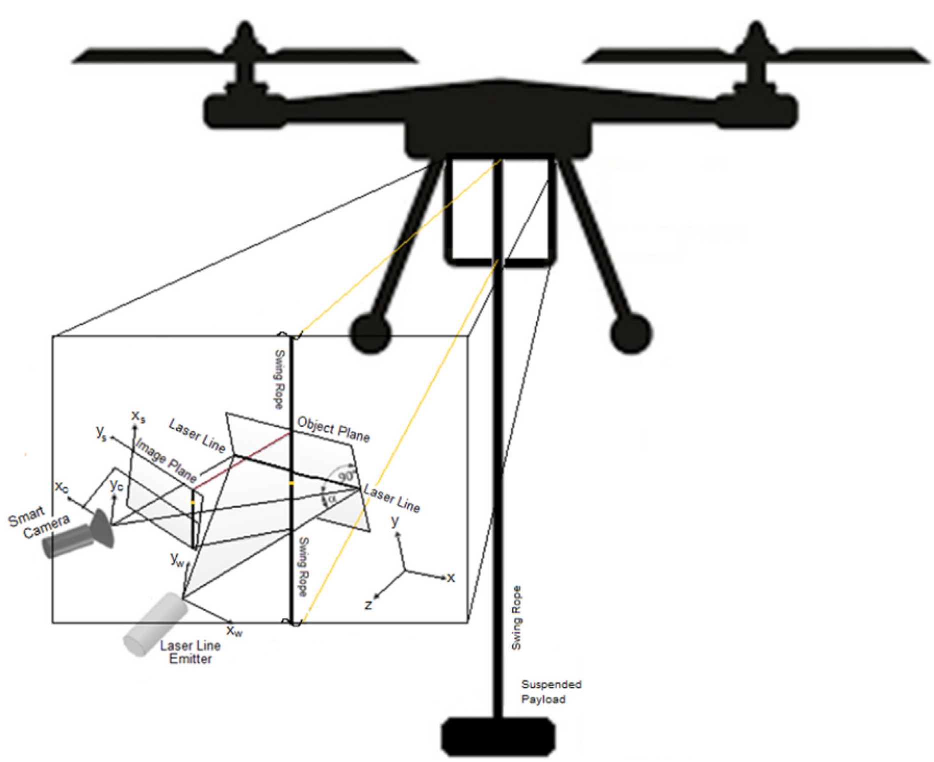

Fig. 8 Proposed swing angle measurement scheme using Laser marking and smart camera sensing technique (Inset [164]).

Table 3 Summary of Multirotor testbed and testing information reported in the literature.

Platform Degrees of Freedom	Comments/Additional Details	Vehicle Type in Reported test	Vehicle mass used in Various Platforms	Reference	Vehicle Suspended Load Status
One Degree of Freedom	A one-axis control test bench is used to tune PID controllers.	Quadcopter	Small vehicle 0.5–4 kg	[173]	Vehicles without Suspended load
	Single-axis Quadcopter control test	Quadcopter	Small vehicle 0.5–4 kg	[174]	
Three Degrees of Freedom	Test platform with control loop structures based on the gyroscopic idea utilized in stability testing for both under and over actuated UAC.	Quadcopter	Small vehicle Approx. 1.6 kg	[175]	
	Test platform for controller design in which rotation about two axes (two of the three axes; yaw, pitch and roll) is restricted and simultaneously translation in the vertical direction is allowed.	Quadcopter	Small vehicle 2.9 kg	[176]	
	Three degree of freedom gyroscopic test platform for assessing vehicle control system	Quadcopter	Small vehicle 0.5–4 kg	[177]	
	Three degree of freedom test platform in which the rotation about the three axes is allowed whereas translation is restricted. Used for testing stabilization of quadcopters with modified PID controller.	Quadcopter	1.3 kg	[178]	
Four Degrees of Freedom	Gyroscopic test platform with four axes motion including roll, pitch, yaw and roll for tuning control parameters.	Multi-rotor UAV	Small vehicle 0.5–4 kg	[179]	
	Three degree of freedom platform with unrestricted rotation about all three axes and the translation is restricted. An additional one degree of freedom platform accompanies the first platform.	Quadcopter	1.2 kg	[180]	
	Test platform with variable degrees of freedom for testing vehicle control systems. The platform allows for yaw, roll, pitch, and elevation. The platform has an adjustable universal joint and bearings to allow a total of four degrees of freedom.	quadcopter	Small vehicle 0.5–4 kg	[181]	
Six Degrees of Freedom	Test platform allowing for rotation about the roll, pitch and row axes as well as translation in 3 direction.	Quadcopter	Small vehicle Up to about 5 kg	[182]	
	Six degree of freedom test platform used in developing hovering algorithm.	Quadcopter	Small vehicle Up to about 5 kg	[183]	
	Test platform allowing for six degree of freedom motion for evaluating the performance of attitude and position cogntrollers of multicopter vehicles.	Multicopter/ Quadcopter	1.8 kg	[184]	
	Test platform with six degrees of freedom used to mimic free flight where the vehicle is attached to the end of a manipulator.	Quadcopter	Small vehicle 0.5–4 kg	[185]	
	Six degrees of freedom test platform that utilizes six axes force torque sensors that aid in simulating the vehicle position.	Quadcopter	Small vehicle 0.5–4 kg	[186]	
Free flight without any restrictions	Evaluation of an anti-swing controller for a quadcopter with an attached suspended load, conducted in an indoor cage. Implementation of an anti-swing controller on a quadcopter with a suspended load. Test conducted indoor in a cage	Quadcopter	Small vehicle 0.5–4 kg	[187]	Vehicles with Suspended load
	Indoor cage quadcopter testing for a trajectory tracking controller.	Quadcopter	Small vehicle 1.6 kg	[188]	
	Indoor multiple multicopter testing of controllers for collaborative transportation of a suspended load.	Quadcopter	Small vehicle 0.15 kg	[60]	
	Testing of a controller implemented on a Hummingbird quadcopter. The test was to validate the controller performance on the quadcopter for carrying a suspended load through a window.	Quadcopter	Small vehicle 0.5–4 kg	[189]	

plane, and with proper geometric indirect decoding it can is converted to swing angles in both required axes [164].

4. Testing techniques

Developing and testing algorithms for autonomous vehicles in the real world is an expensive and time-consuming process. Prior to the real flight of the UAV, quad-rotor UAV simulations need to be performed to reduce the risk of property damage resulting due to airframe crashes, system failure, or controller malfunction. To prevent these problems from occurring, different simulations can be done such as numerical simulations, software in the loop simulation (SILT), Hardware in The Loop (HITL) simulation, and actual tests on testbeds. All of this makes it possible to test and build multirotor vehicles in a safe and cost-effective manner.

4.1. SITL and HITL

SITL simulation relies mainly on a separate computer where the flight code is simulated completely along with the sensor model and vehicle dynamics to provide similar results to what the real-life experiment would behave and is used mainly during the development stage of the simulation model. The SITL platform relies on UDP and TCP communication among its various parts, this communication is mainly governed by what is known as Lockstep stepping, which is a technique developed to synchronize all the simulator parts together to avoid any packet loss or desynchronization between them. Lockstep issues a command for each cycle done by the controller to mimic the real operation in real life.

HITL is an excellent solution to measure the performance of the deployed models and algorithms on real flight hardware. The HITL simulations run the flight code and algorithms on the real-time computer and simulate the vehicle dynamics on the host computer and feeds the data through a Serial connection and then visualize the received responses [165].

Most of the HITL systems are developed for simulating the quadrotor only [166–169]. Recently, SITL simulations with Gazebo and PX4 were conducted by Graham [170] for a quadrotor with a suspended load. The intentions were to test his design landing system but no comparison between the Simulink and SITL simulations has been done. However, no HITL simulations for the quadrotor have been demonstrated. Therefore, it is required from the researchers to fill this gap.

4.2. Multirotor vehicle testbeds

Most of the published papers that addressed the design of testbed for flight vehicles are related to hardware in the loop (HITL) flight test which cannot be considered as real flight test because the sensors that provide the vehicle states are not real in HITL [168,169,171,172]. There are, however, a number of published papers that address the issue of testbeds for multirotor testing. single-axis test platforms are reported in [173,174]. Although they have restricted functionality because they only permit motion (rotation) around one axis, these test platforms have been utilized for control testing, including PID controller tuning. Testbeds inspired by gyroscopes have also been proposed for control tests. These include testbeds with 3 DOF (allowing motion about the yaw, pitch, and roll axes) [175–178] as well as 4 DOF (allowing motion about the yaw, pitch, roll axes, and elevation) [179–181]. Testbeds with the capability to allow for 6 DOF have also been proposed and used for control tests as documented in [182–186]. These testbeds have made the experiments more realistic and similar to what would be expected in free flight, with proper constraints in place to avoid collisions and accidents. A summary of the testbeds and corresponding test information is presented in Table 3.

The testbeds mentioned above have been employed in the development of multirotor vehicles with the purpose of preventing accidents, property damage, and loss of life. These test platforms were primarily designed and built to test vehicles without suspended loads. A search in the literature for testbeds for testing multirotor with suspended loads proved futile. Instead, flight tests for multirotor with suspended loads are conducted unrestrictedly (free flight) as reported in [60,187–189] and summarized in Table 3.

As previously stated, it appears that little or no effort is being made to develop testbeds for multirotor vehicles with suspended loads. Reported tests for anti-swing controller developments [187,189], swing load trajectory tracking [188], multivehicle collaborative swing load transportation [60] have all been conducted without a testbed. While these tests were reported to have been conducted successfully, there remains a risk of faulty controllers that can cause accidents in future developments. As a result, the authors believe that developing testbeds for multirotors with suspended loads is required to mitigate the risk of accidents.

5. Conclusion

In this study, recent scientific work related to developing and implementing control systems for quadrotors with suspended loads is reviewed. It was observed that the majority of developed control algorithms are geared to suppress suspended load oscillations by generating swing-free flight trajectories without payload status feedback. The performance of these controllers may deteriorate with the existence of external disturbances to the suspended load. To prevent load oscillations, more effort should be put into designing an anti-swing controller that uses load swing angles as feedback signals. Therefore, the techniques of the advanced control theory such as the anti-disturbance control, adaptive dynamic programming, and deep learning control are recommended as the new directions for controlling the quadrotor with a suspended load.

A complete overview of the hardware platform (HP) used in previous related research works on autonomous flight control with suspended load was presented. The available open-source HPs choices from four mainstream platform categories (FPGA, ARM, ATML, and Raspberry Pi) have been explored for their processing capabilities, sensors composition, and interfaces. Based on the technical aspects related to autonomous flight with suspended load and available choices, it is recommended by the authors that Pixhawk autopilot is to be considered for controller implementation since it has all the attributes needed for successful implementation of the designed controller and is supported by both Matlab and Simulink software. In the Simulink environment, the controller may be created, and then uploaded to the Pixhawk. Monitoring and recording the system's performance may be accomplished using the mission planning software with telemetry.

Furthermore, to integrate swing angle to the designed autonomous flight controller, as there is a limited amount of available published data (mostly for indoor applications), the best possible swing angle measurement architectures, configurations, research directions and key challenges related to each scheme has been discussed to help the researchers to bring considerable research efforts, with the target that this technology can lead towards full growth advancement. For each proposed, scheme technical and non-technical obstacles are also discussed. Keeping into consideration that the main objective of autonomous flight with suspended load is for outdoor applications, the authors would recommend an Attitude and Heading reference system (AHRS) based swing angle measurement scheme as the best solution. This is because of inherent attributes (economic, light weight, highly sensitive, and having the capability of integration with onboard Hardware platform by wired and wireless link) associated to recent developments in AHRS technology.

Testing platforms for multirotor vehicles play a central role in the development of these vehicles. In particular, they have been used in evaluating the performance of controllers as well as PID controller tuning for these vehicles without the risk of costly and dangerous crashes. These testbeds are generally categorized according to the related DOF. As previously outlined, 1 DOF, 3 DOF, 4 DOF, and 6 DOF appear to be the most commonly used test platforms. According to the literature, these testbeds were created to accommodate vehicles without suspended loads. For vehicles with suspended loads, experiments have been conducted through unrestricted flight. There thus appears to be a gap in the literature for test platforms for vehicles with suspended loads. It is therefore the opinion of the authors, that there is a need for emphasis on the development of testing platforms for vehicles with suspended loads.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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