Operational Safety Analysis and Controller Design of a Dual Drones System

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***Abstract*—This paper describes the operational system analysis and controller design of a dual drone system. The system is considered as a cascade connection of uncertain nonlinear system. The analysis is conducted to ensure increased operational safety as it is important for successful flight missions. The paper also addresses the problems, when drones are used in practice, in particular in the area of search and rescue, military and scientific studies. A robust control approach is considered for the control law development. The controller is designed to ensure the stabilization of the drone system in order to successfully fulfill missions.**

***Keywords*—unmanned vehicle; controller design; stabilization; operational safety; drones system**

I. Introduction

Recently, research on drone systems has gained great attention in the aerospace research community due to its ability to cope with many different applications, such as space science, defence, search and rescue etc. Importantly, in the case of search and rescue operation, when lives are under risk and rapid rescue operations are needed this kind of dual drone system operation (Figure 1) is vital.

Fig.1. Dual drones system

In this paper a single master and slave drone system configuration is considered; where a large drone is used as a master and a small drone acts as a slave (see Figure.1). Therefore, the generic problem of tracking a prescribed path by a slave relative to the master is tackled.

The research studies of the reported controller design methods on drones systems evidenced that the drone's system operation and its controller design are very active research areas [1]. The research in this area is mainly motivated by the factor that the current control methods cannot provide full satisfaction to the desired design requirements in terms of quality, stability, robustness and so forth.

The progress to date in this general area can be summarized by stating that basic feedback control laws which can meet the requirements are feasible [2, 3]. It is timely therefore to consider other requirements that are critical to the success of any proposed mission involving drones whilst in flight. In this paper the emphasis is on system configuration and analysis for a better controller design to resolve the problems when drones are used in search and rescue operations.

The purpose of control system design is to achieve higher survivability even if faults occur during the operation. The possible faults and errors a mission could be required to survive include, for example, error by the operator, error in operational procedures, hardware degradation faults, design faults and environmental stress. Hence if assured, secure and automated reconfiguration is possible then it could be possible to protect the overall mission against such faults and threats.

Based on the considerations such as those summarized above immediately leads to the requirement that the control system should have the ability to redesign or adjust, in order to recover from any degradation type faults that may occur during a flight mission. In the present study, at first, the drone system modelling and the common defects that occur with a pair of drone's system operation are described. It therefore follows the possible controller design to overcome such problems. Finally, concluding remarks and discussions are presented.

II. System Modelling and Analysis

Considering the control of a dual drone system, the dynamical model of the system has terms which are uncertain. Uncertainties may arise from the master to carry the slave or the immeasurable parameters in the dynamical model. Additional uncertainties may also arise from computational errors of the dynamic effects resulting from aerodynamics. Therefore for a realistic model of potential uncertainties must be taken into account during the flight controller design.

A commonly used mathematical model of a quadrotor model presented in the literature is used [4, 5, 6] in this work to obtain a mathematical model of a dual drone system. Utilizing system modelling, firstly, the slave (smaller drone to that of its parent) is considered to be an externally slung load of the master (larger drone) with a single suspension point that is subject to motion and therefore modelled as a point mass or a driven spherical pendulum. The equations that describe the load dynamics are obtained by first considering motion with reference to the longitudinal suspension angle θ_L in the x-z plane (Figure 1). This is then repeated for the lateral case involving φ_L and the y-z plane. These are then combined to obtain the model for the motion of the load. The under-slung load system has six inputs, longitudinal, lateral, and vertical velocities together with the corresponding accelerations of the master, whilst the outputs are the longitudinal and lateral directional suspension angles. The load is subject to an isotropic aerodynamic force (proportional to the square of its airspeed) such as would be experienced by a spherical shaped load. Aerodynamic interaction with the master has been ignored. Finally, the sling itself is assumed to contribute zero aerodynamic force of its own. With these assumptions, the equations governing the slave (load) motion can be derived as follows.

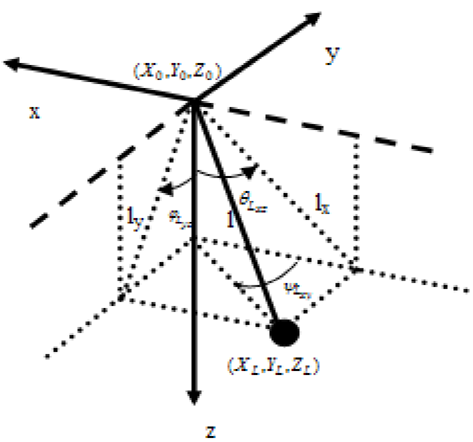

Fig.2. Coordinate system for the slave motion in the XYZ plane.

Considering the motion in the x-z plane, the load position with respect to the coordinate system in Figure 2 can be written as follows;

$$X_L = X_0 - l_x \sin\theta_L \quad (1)$$

$$Z_L = Z_0 + l_x \cos\theta_L \quad (2)$$

the resolved accelerations of the load are

$$\ddot{X}_L = \ddot{X}_0 + l_x\dot{\theta}_L^2 \sin\theta_L - l_x\ddot{\theta}_L \cos\theta_L \quad (3)$$

$$\ddot{Z}_L = \ddot{Z}_0 - l_x\dot{\theta}_L^2 \cos\theta_L - l_x\ddot{\theta}_L \sin\theta_L \quad (4)$$

So, using equations (1) – (4) longitudinal suspension angle acceleration $\ddot{\theta}_L$ can be calculated as follows:

$$\begin{aligned}\ddot{\theta}_L = &-\frac{g}{l_x}\sin\theta_L + \frac{\cos\theta_L}{l_x}\ddot{X}_0 + \frac{\sin\theta_L}{l_x}\ddot{Z}_0 \\ &+ \frac{k_D sign(\dot{X}_L)\cos\theta_L}{M_L l_x}\dot{X}_0^2 + \frac{k_D sign(\dot{Z}_L)\sin\theta_L}{M_L l_x}\dot{Z}_0^2 \\ &- \frac{2k_D}{M_L}\left(sign(\dot{X}_L)\cos^2\theta_L \dot{X}_0 + sign(\dot{Z}_L)\sin^2\theta_L \dot{Z}_0\right)\dot{\theta}_L - k_\theta\dot{\theta}_L \\ &+ \frac{k_D l_x}{M_L}\left[sign(\dot{X}_L)\cos^3\theta_L + sign(\dot{Z}_L)\sin^3\theta_L\right]\dot{\theta}_L^2 \end{aligned} \quad (5)$$

Define $\tilde{\theta}_L = \left[\theta_L \;\; \dot{\theta}_L\right]^T = \left[\theta_{L1} \;\; \theta_{L2}\right]^T$ then using (5) the slave model can be rewritten as follows:

$$\dot{\theta}_{L_1} = \theta_{L_2} \quad (6a)$$

$$\begin{aligned}\dot{\theta}_{L_2} = &\frac{-g}{l_x}\sin\theta_{L_1} + \frac{k_D l_x}{M_L}[sign(\dot{X}_L)\cos^3\theta_{L_1} + sign(\dot{Z}_L)\sin^3\theta_{L_1}]\theta_{L_2}^2 - k_\theta\theta_{L_2} \\ &+ \left(\frac{k_D sign(\dot{X}_L)\cos\theta_{L_1}}{M_L l_x}\right)\dot{X}_0^2 + \left(\frac{k_D sign(\dot{Z}_L)\sin\theta_{L_1}}{M_L l_x}\right)\dot{Z}_0^2 \\ &+ \frac{\cos\theta_{L_1}}{l_x}\ddot{X}_0 + \frac{\sin\theta_{L_1}}{l_x}\ddot{Z}_0 \\ &- \frac{2k_D}{M_L}\left(sign(\dot{X}_L)\cos^2\theta_{L_1}\dot{X}_0 + sign(\dot{Z}_L)\sin^2\theta_{L_1}\dot{Z}_0\right)\theta_{L_2} \end{aligned} \quad (6b)$$

Equations (6a and 6b) represents the longitudinal motion of the slave. Similarly for the lateral motion in the Y-Z plane, by defining $\tilde{\varphi}_L = \left[\varphi_L \;\; \dot{\varphi}_L\right]^T = \left[\varphi_{L_1} \;\; \varphi_{L_2}\right]^T$ then the slave system model can be obtained as follows;

$$\dot{\varphi}_{L_1} = \varphi_{L_2} \quad (7a)$$

$$\begin{aligned}\dot{\varphi}_{L_2} = &\frac{-g}{l_y}\sin\varphi_{L_1} + \frac{k_D l_y}{M_L}\left[sign(\dot{Y}_L)\cos^3\varphi_{L_1} + sign(\dot{Z}_L)\sin^3\varphi_{L_1}\right]\varphi_{L_2}^2 - k_\varphi\varphi_{L_2} \\ &+ \left(\frac{k_D sign(\dot{Y}_L)\cos\varphi_{L_1}}{M_L l_y}\right)\dot{Y}_0^2 + \left(\frac{k_D sign(\dot{Z}_L)\sin\varphi_{L_1}}{M_L l_y}\right)\dot{Z}_0^2 \\ &+ \frac{\cos\varphi_{L_1}}{l_y}\ddot{Y}_0 + \frac{\sin\varphi_{L_1}}{l_y}\ddot{Z}_0 \\ &- \frac{2k_D}{M_L}\left(sign(\dot{Y}_L)\cos^2\varphi_{L_1}\dot{Y}_0 + sign(\dot{Z}_L)\sin^2\varphi_{L_1}\dot{Z}_0\right)\varphi_{L_2} \end{aligned} \quad (7b)$$

Equations (7a and 7b) represents the lateral motion of the slave. Finally, the load angle ψ_L in the X-Y plane can be obtained as follows;

$$\psi_L = \tan^{-1}\left(\frac{\tan\varphi_L}{\tan\theta_L}\right) \quad (8)$$

hence $\dot{\psi}_L$ and $\ddot{\psi}_L$.

From equation (8) the yaw angle and the motion in X – Y plane can be obtained. Equations (6) – (8) represent the slave system model.

Now, the master drone is considered as the second subsystem. In order to establish the dynamic model of the master drone, the quadrotor symmetrical rigid body system with body B(xyz) to earth E(XYZ) co-ordinates with Euler angles transition of (XYZ) is used (Figure 3).

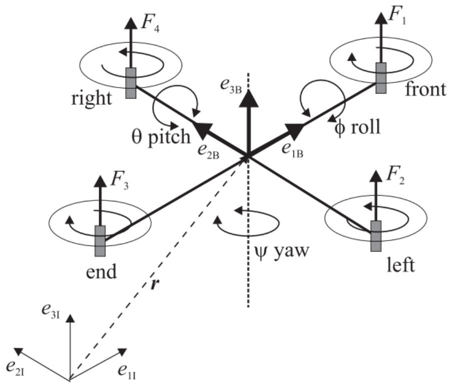

Fig.3 the coordinate systems used [7].

Therefore the transition matrix R_{xyz} can be written as;

$$R_{xyz} = \begin{bmatrix} c(\psi)c(\phi) & c(\psi)s(\theta)s(\phi) & c(\psi)s(\theta)c(\phi)+s(\psi)s(\phi) \\ s(\psi)c(\theta) & s(\psi)s(\theta)s(\phi) & s(\psi)s(\theta)c(\phi)-s(\phi)c(\psi) \\ -s(\theta) & c(\theta)s(\phi) & c(\theta)c(\phi) \end{bmatrix} \quad (9)$$

Where, $c() = \cos()$ and $s() = \sin()$

Define;

$$\vec{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} \quad \vec{\omega} = \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

with $\vec{W} = mg$, $D_i = \frac{1}{2}\rho C_d \omega_i^2 = k_t \omega_i^2$ and $L_i = \frac{1}{2}\rho C_t \omega_i^2 = k_t \omega_i^2$

Therefore, using the above information and equation (9), the line motion of the quadrotor with u, v, w are the velocities in the (xyz) direction can be obtained as;

$$\begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \end{bmatrix} = Q_L \begin{bmatrix} (c(\psi)s(\theta)c(\phi)+s(\psi)s(\phi)) - k_1 u \\ (s(\psi)s(\phi)c(\phi)-c(\psi)s(\phi)) - k_2 v \\ (c(\theta)c(\phi) - k_3 w) - g \end{bmatrix} \quad (10)$$

Where, $Q_L = \dfrac{k_t}{m}\sum_{i=1}^{4}\omega_i^2$

The quadrotor has been assumed to be symmetrical in structure; therefore the inertia matrix I can be defined as a diagonal matrix;

$$I = \begin{bmatrix} I_x & 0 & 0 \\ 0 & I_y & 0 \\ 0 & 0 & I_z \end{bmatrix} \text{ with } \vec{M} = \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix}, \text{ and } \sum M = I \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix}$$

Using this information, angular motion equations can be obtained and by combining with the line motion equation (10) the nonlinear motion equations (11) of quadrotor can be written as;

$$\begin{aligned} \dot{u} &= Q_L\big(c(\psi)s(\theta)c(\phi) + s(\psi)s(\phi)\big) - \tfrac{k_1}{m}u \\ \dot{v} &= Q_L\big(s(\psi)s(\phi)c(\phi) - c(\psi)s(\phi)\big) - \tfrac{k_2}{m}v \\ \dot{w} &= \big(Q_L\big(c(\phi)c(\theta)\big) - \tfrac{k_3}{m}w\big) - g \\ \dot{p} &= \big[M_x + \big(I_y - I_z\big)qr\big]I_x^{-1} \\ \dot{q} &= \big[M_y + (I_z - I_x)rp\big]I_y^{-1} \\ \dot{r} &= \big[M_z + (I_x - I_y)pq\big]I_z^{-1} \\ \dot{\phi} &= \big(p + qs(\phi)t(\theta) + rc(\phi)t(\theta)\big) \\ \dot{\theta} &= qc(\phi) + rs(\phi) \\ \dot{\psi} &= \big(qs(\phi) + rc(\phi)\big)/c(\theta) \end{aligned} \quad (11)$$

With control input $\vec{U} = [U_1 \quad U_2 \quad U_3 \quad U_4]^T$ and U_1 is the vertical speed control input, U_2, U_3 and U_4 are the roll, pitch and yaw control inputs. The control inputs can be calculated as;

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} F_1 + F_2 + F_3 + F_4 \\ F_4 - F_2 \\ F_3 - F_1 \\ F_2 + F_4 - F_3 - F_1 \end{bmatrix} \quad (12)$$

Equation (12) represents the control inputs, now by applying the small perturbation method the linear quadrotor model equation (13) can be obtained, which is expressed in the state space form:

$$\dot{\bar{x}}_Q(t) = A\bar{x}_Q(t) + B\bar{u}(t) \quad (13)$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & x_\theta & 0 & x_u & 0 & x_w & 0 & x_q & 0 \\ y_\varphi & 0 & 0 & 0 & y_v & 0 & y_p & 0 & y_r \\ 0 & z_\theta & 0 & z_u & 0 & z_w & 0 & z_q & 0 \\ l_\varphi & 0 & 0 & 0 & l_v & 0 & l_p & 0 & l_r \\ 0 & m_\theta & 0 & m_u & 0 & m_w & 0 & m_q & 0 \\ n_\varphi & 0 & 0 & 0 & n_v & 0 & n_p & 0 & n_r \end{bmatrix} \begin{bmatrix} \phi \\ \theta \\ \psi \\ u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ x_t & 0 & 0 & x_\delta \\ 0 & y_\delta & y_t & 0 \\ 0 & 0 & 0 & z_\delta \\ 0 & l_\delta & 0 & 0 \\ 0 & 0 & 0 & m_\delta \\ 0 & n_\delta & 0 & 0 \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix}$$

It should be noted that, for the dual drone system, the nonlinear system model is governed by the equations (6) – (8) and (11).

III. Controller Design

The interest in designing a controller for a drone system has gained considerable attention in the last few decades [1, 3, 5]. Choosing the control technique depends on the control target the vehicle must meet [2]. There are many important possible flight missions, such as; stabilization at hover condition, straight line trajectory, complex manoeuver, collision avoidance, pickup, loading and releasing object, take-off and landing need to be controlled properly, since the system is an uncertain dynamical system.

A survey of reported methods for quadrotor control law design shows that many approaches used to design the control law have involved the application of loop control [2]. The controller design methods such as linear quadratic regular (LQR) or linear quadratic Gaussian (LQG) method, commonly referred to LQ methods [7, 8, 9], and sliding mode control [10, 11] are used to evaluate multivariable control law design for quadrotor systems. The main idea of sliding mode control is to maintain the system sliding on a surface in the state space despite the uncertainties or perturbations. This is done by means of a discontinuous control law that switches between two structures, when the system passes through that surface [12]. Many researchers using the idea of sliding mode control to develop drone system flight control laws, see for example [13]. Sliding mode control is a technique for the design of nonlinear regulators. The first step in the two part synthesis procedure is to specify a desired sliding subspace. This involves using regulation techniques such as LQR to stabilise a reduced order system. A nonlinear controller is then developed in the second step to asymptotically drive the system towards the regulated subsystem so-called sliding subspace. However, designing the sliding subspace is very difficult job indeed, since there appears to be little guidance on how to design a sliding subspace, which may limit this design method to quadrotor control applications [14].

The method like H_∞ optimisation used to design a flight control law can be considered as a frequency domain method, since this technique is similar to that the design of the control law is based on a transfer function matrix representation of the system and it involves frequency domain performance specifications [15, 16]. Quantitative feedback control technique is a control synthesis technique which involves shaping the loop transmission to meet bounds placed upon it by performance specifications in terms of desired system responses and disturbance rejection levels [17].The possibility of applying Quantitative feedback control technique to quadrotor flight control design is considered by several researches see for example [17, 18]. However, due to the requirements of conservative and sequential design for each of the multivariable sub-systems it is difficult to obtain best closed loop performance under practical constraints. Moreover, manual bound computation and trial and error loop shaping design procedures makes difficult to realise a stabilising feedback control law for quadrotor system using quantitative feedback control technique.

Model reference techniques are those synthesis procedures which can be used to design feedforward controllers. For instance, integral inverse model following technique and controllers using nonlinear system inverses are can be considered as model reference techniques. In the case of integral inverse model following technique a regulator is designed to minimise the error transients between the responses of the system being controlled and a model which describes dynamics. The controller using nonlinear system inverses is essentially a procedure for the inversion of the system such that each input is linked with an output [19].

State estimator techniques such as the Kalman filter and state observer and loop transfer techniques can be classified as output feedback methods. State estimator techniques provide a means of generating estimated state variables for feedback from available measurements. However, the use of this method has a row back is that the use of estimated state feedback can create problems for the designer in that the resulting control laws are not, in most cases, robust to uncertainties or variations in the plant [6].

The use of intelligent control methods for quadrotor control system design such as fuzzy control and Neural Network (NN) has also been addressed by several researchers for example see, [20, 21].

From the review of popular quadrotor system control methods, it is clear that considerable attention has been paid to the design of a controller to obtain a satisfactory result. The control problem has been tackled using different approaches ranging from linear quadratic control [9], sliding mode control [14], adaptive control [22], feedback linearization [23], tracking control [24], and backstepping based PID control [25]. Apart from the methods emphasized above, many other techniques are reported for complex modern control system design.

In general there are two main approaches for control of uncertain dynamical systems, that is, deterministic and stochastic control. If the uncertainty in the system model is assumed to have statistical characterization and the desired behaviour of the system is described in a statistical sense a stochastic approach is feasible; otherwise, if structural properties and bounding conditions relating to the uncertainties are known, a deterministic approach is appropriate. Deterministic feedback control of uncertain dynamical systems proposes the use of determined linear or nonlinear feedback control functions, which operate effectively over a specified magnitude range of system parameter variations and disturbances, without any on-line identification of the system parameters. The benefit of such an approach is that no statistical information of the system variations is required to yield the desired dynamic behaviour and, hence, the controller may have a simple structure for implementation in practical systems. However the deterministic control design methodology requires the system state vector is available for measurements, and the bounding knowledge of uncertainties are known, which may put restrictions on the applications of this method.

Considering the two models described in section 2, a mathematical model for the dual drone system can be obtained. If the velocities and accelerations of the master are considered as the inputs to the slave, the combined system model will have a structure of a cascade connection of the two subsystems, therefore the system will have the following format.

$$\dot{x}(t) = f\left(x(t)\right) + G\left(x(t)\right)\tilde{u}\left(t\right) \tag{14}$$

Where $x(t) \in \mathrm{R}^n$, $\tilde{u} \in \mathrm{R}^m$. In general mathematical models of dynamical systems are usually imprecise due to modelling errors and exogenous disturbances. Equation (14) can be considered as the nominal part of the system model and the uncertainty can be modelled by as an additive perturbation to the nominal system model, more specifically, the structure of the system has the form:

$$\dot{x}(t) = f(x(t)) + G(x(t))\tilde{u}(t) + \vartheta(x(t), u(t)) \tag{15}$$

Where $\vartheta(x(t), u(t))$ models the uncertainty in the system.

So, using the kind of nonlinear system structure described in equation (15) a nonlinear deterministic controller can be designed for the dual drone system. The key advantage of this control method is that the controller design takes the system uncertainty into account. The controller can give a guaranteed stability region for the systems considered. This method should have the potential for solving some problems arising in quadrotor system control.

IV. Experimental Study

The development of a control system for the pair of drone system requires the development of an adequate test-bed setup for the experimental study. Recently, many set-ups have been designed and built to provide required condition for conducting experimental tests on quadrotor and for evaluating the performance of the vehicle. Set-ups and experiments can be divided into three categories: aerodynamics, attitude and altitude control, and six-degrees of freedom motion control.

A set-up is built to provide six degrees of freedom motion for the dual drone system. It's allows the master (quadrotor) to rotate on its yaw, pitch, and roll axes and move vertically while for the slave (load) pitch and roll movement can be measured. The prototype system currently utilises the master drone with a weight of 10kg, the body dimensions comprise of a height of 50cm and a width and depth of 1000cm. The wing span or propeller to propeller dimension (tip to tip) is 1762cm. The available thrust totals 62kg across all 4 rotors giving a capable payload of 20kg. The remaining available thrust of 32kg is reserved for flight and stability during hover functions, the total cost of the basic build is approximately £4000.

The slave drone current weight is 1kg and is spherical with an outer radius of 15cm. The shape of the slave drone allows for damage resistance and docking options that are not possible with conventional drone structures. It is capable of 6.8kg of thrust giving a capable payload of 2.4kg which allows for optional equipment to be carried for the use in search and rescue, military or scientific applications. Typically this could include high zoom cameras, infra red camera, additional power packs for extended flight time, measurement equipment such as sensors and more. The basic cost of the prototype slave drone is £600 with no additional equipment mentioned (Figure 4).

The Master drone can be used to carry the slave into environments where it would be unrealistic for the slave to approach unassisted, such as over large flight times or hostile conditions such as high winds. The slave can then undock and perform functions that would be unfeasible for the master, these can include tight spaces or situations where the potential loss of the master would be too costly to perform such a risky mission. Flight data from the slave can be relayed back to the master reducing the communications distance to the user and reduce the power requirements of the slave communications. Lower cost drones of less than £50 are achievable and considered disposable for the current research purposes. This gives promise to data collection with greatly reduced cost thus allowing data to be collected in environments where it may have been not viable, such as volcanoes, war zones, tornados and the like.

At its simplest a dual drone system allows for increased flexibility during missions, with the master drone primary function to transport slave drones to the mission site and store or relay the slave drone data collection as well as relay user flight control such as roll, pitch, yaw and thrust to the slave utilising the increased sensitivity of the larger more powerful antenna capability of the master drone. Progressing the research further multiple slaves can be docked to the master. Slave drones can be custom built for the environment and loaded to the master at short notice allowing for rapid deployment of drone swarms that are customised to the mission. For example should a situation arise where a chemical hazard is suspected it will be possible to load the master drone with a slave drone capable of detecting such a chemical that can be sent into the hazardous area, this allows the master drone to fore fill its function of flying greater distances than the slave would be capable of thus maintaining the safety of the operating crew and yet massively reduce financial loss should the drone fail to return to the master drone. Data can be stored or relayed through the master which would allow for a greatly improved success rate of returning the critical data back to the mission crew. Similarly slave drones with cameras could undock and monitor the mission from a different perspective if only a single master drone was utilised which is typical of the current technology.

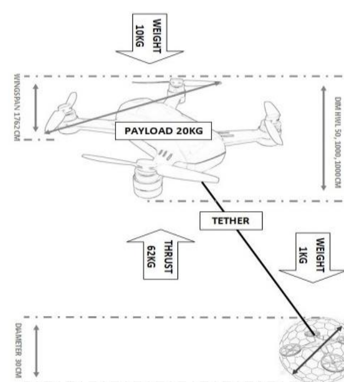

Fig.4 diagram of prototype dual drone system.

Future research could create autonomous drone swarms that rapidly relay captured photos of areas at close proximity useful in military applications where gun fire may be present. The financial loss of a slave drone can be considered negligible in comparison to the collected data. Typically in such situations a larger and extremely expensive master drone takes aerial images with high zoom cameras. Arguably low cost camera photographs at ground level would provide more valuable data in such situations. These autonomous rapid moving drone swarms due to their minimal physical size and reduced weight would be extremely difficult to disable allowing for greater success rates, such slave drone flight times would be minimal at around 20 minute flight time but capable of reaching speeds of 100mph. Flight patterns of such drones would be similar to that of a dragon fly where they would fly at high speeds to a hover, capture imagery and move on.

V. DISCUSSION AND CONCLUDING REMARKS

This paper describes the modelling and controller design of a dual drone system. A single master and slave drone's system configuration is considered; where a large drone is used as a master and a small drone as a slave. Therefore, the generic problem of tracking a prescribed path by a slave relative to the master is tackled. To simplify the analysis, only the case of system stabilization at hover condition with straight line trajectory is considered for docking and pickup.

A typical case of slave docking to the sling offered by the master, that is attached to a single point of suspension is considered. The lower end of the sling (string) is attached with a special (magnetic) docking mechanism, that's allow the slave to be docked, when its located to the specified position or its neighbourhood. It should be noted that, once the docking to the sling is completed, the master winches the string and docks the slave within it. In this paper the modelling analysis only investigates the system behaviour after the slave is docked into the sling.

In the on-going research work, further investigation is carried out, in order to remove the use of sling for the docking and pickup. Alternatively, advanced technologies such as lasers and sensors are used to identify the straight line of trajectory and the specified position within the stability margin. It requires the slave to move in the line of trajectory towards to the master. Another possible way of tackling the problem is using the advanced system reconfiguration methods such as reconfigurable adaptive control techniques. This requires the master and slave to auto-reconfiguration to carry out the mission successfully.

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