BUILDING A TESTBED FOR MINI QUADROTOR UNMANNED AERIAL VEHICLE
WITH PROTECTIVE SHROUD

A Thesis by

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I have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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DEDICATION

To my family
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ABSTRACT

Potential applications of small rotorcraft unmanned aerial vehicles (UAVs) range from military missions to exploration of the planet Mars (Patrick C. O’Brien, 2003). Tasks such as exploration of unknown territories, formation flying, intelligence gathering etc, require UAV to be capable of flying very close to other flying or steady objects. Exposed rotary wings limit rotorcraft vehicle’s capability to fly in proximity of other objects. In some applications, such as rescue operation, urban warfare etc, it is highly desirable to cover exposed blades of rotorcraft UAV.

This thesis work proposes a testbed for a mini rotorcraft UAV with protective shroud to demonstrate the capability of a rotorcraft to continue its flight after an impact with other object in environment, e.g. building wall. The quadrotor configuration is considered as a base vehicle for the testbed. A protective shroud for base vehicle is designed and built to protect rotors against the impact with wall. A closed loop attitude stability controller is developed and tested to ensure the stability of vehicle against high frequency vibrations from the rotors and disturbances from the impact. Experiments are carried out to prove the stability of the quadrotor vehicle after an impact with a building wall.
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CHAPTER 1
INTRODUCTION

1.1 Overview

Today’s integrated technology has opened many new areas of application for Unmanned Aerial Vehicles (UAVs). Completing complex and/or risky missions without any onboard human involvement is the biggest advantage of UAVs. Applications of UAVs range from military missions to exploration of the planet Mars [1]. Researchers have also started considering UAVs for commercial applications, e.g. a loading and unloading vehicle for fishing industry [2]. Though UAVs are mostly known for their military applications, there are about 1565 UAV helicopters, out of the 2400 total estimated UAVs worldwide, used for agricultural purposes in Japan [3]. With new technical advances, affordability and acceptability of UAVs will increase, which will fuel the interest of researcher and entrepreneurs to explore more and more applications for UAVs.

In many applications, Vertical Take-Off and Landing (VTOL) vehicles, also known as rotorcraft vehicles, are preferred over fixed wing vehicles because of their higher maneuverability. Also they require less launching and landing support compared to fixed wing vehicles. Tasks such as exploration of unknown territories, formation flying, intelligence gathering etc, require rotorcraft UAV to be capable of flying very close to other flying or stationary objects. Because of exposed rotary wings, rotorcraft UAVs are very sensitive to the environment they are flying within. In applications such as rescue operation, urban warfare etc, it is highly desirable to cover exposed blades of UAVs. Exposed blades of an UAV can be covered by introducing a rigid protective shroud around the base vehicle, which allows UAV to collide
with other obstacles in environment such as trees, buildings and even other aerial vehicles, without any damage to rotors and vehicle.

Since rotorcraft vehicles are inherently unstable, an active attitude stability controller becomes an important part of the UAV systems [4]. It automatically stabilizes the attitude of the vehicle and prevents the vehicle from flopping over in the absence of pilot inputs and also maintains the desired horizontal orientation [4]. It also allows pilot to do other maneuvers without taking care of attitude stability. Performance of the attitude controller depends on the noise and disturbance level of the system. Addition of protective shroud to the base vehicle may cause some changes in the dynamic behavior of base vehicle by altering the air flow pattern, introducing additional vibration to the system and increasing weight of the overall vehicle. An impact with objects such as brick wall, will introduce a large disturbance to the system. So, it becomes important to ensure the overall stability of vehicle before and after any impact happens with an environmental object.

1.2 Objectives

This research work was carried out as a part of the research project “Design of Protective Shroud for Helicopter”, at Wichita State University, Kansas, which aims to build a cluster of fully autonomous mini UAVs capable of flying while touching with each other and/or brick wall. Also, the UAV should be capable of continuing its flight even after an impact with a brick wall.

This thesis work is divided into two parts. Part I (Chapter 2) addresses the problem of stability of a feedback control system of a double integral plant with impacting contact and velocity measurement only. A simple control law is presented. The objective is convergence to the constant contact maintenance. The contact maintenance in finite time for all (positive) control parameters is proved.
Part II (Chapter 3, 4 and 5) is focused on building an attitude stability controller for a quadrotor vehicle with protective shroud on it, which allows the vehicle to hover without pilot inputs and also prevents the vehicle from flopping over during an impact with a brick wall. Experiments have been carried out to prove the vehicle’s capability to hover after a collision with wall.
PART I
CHAPTER 2

MAINTAINING IMPACTING CONTACT WITH VELOCITY MEASUREMENT ONLY

2.1 Introduction

There is a trend toward using simple and cheaper autonomous and semi autonomous robotic vehicles. The cost reductions often imply fewer sensors on the vehicle. An example includes rotorcraft whose rotors are protected so as to allow collisions with obstacles such as a brick wall. Many such vehicles do not have force sensors, position sensors or proximity sensors. In a semi autonomous or completely autonomous scenario, a collision, such as with the wall of a building, may be an intentional one, with the ultimate goal of maintaining contact with the wall.

In this chapter, the problem of stabilizing the transition from non-contact to contact-maintenance for a vehicle without position, force, or proximity sensors is considered. Semi-autonomous and fully autonomous application cases include tele-operation or self-guided operation in which the vehicle is servoing to a commanded velocity that has a projection normal and into the wall. In this study, initially the acceleration dynamics is neglected and acceleration is considered as a control input. However, the issue of the neglected acceleration dynamics is discussed, including an analysis involving a comparison between the size of the time interval between successive impacts and the time constant of the neglected acceleration dynamics; the range of parameters where the neglected dynamics are insignificant is given and so are relevant illustrative examples demonstrating these ranges.

Most of the research on the transition from non contact to contact has been for fixed-base robotic arms with measurements of position and a nominal estimate of the position of the object to be gripped on or pressed against by the end effector. In this problem of transitioning from
position control to force control, it is well known that the impacts make the transition a difficult problem.

In some of this research for fixed-base robots, the contact is modeled with springs [5, 6]. For hard contact, these springs are extremely stiff, and the controllers must have extremely large bandwidth to be implemented effectively ([5, 7]. Other approaches have assumed the contact is sufficiently stiff to render an instantaneous impact model reasonable. Within the present study, this instantaneous approximation is also made. [8], building on the work of [9] and [10], make this approximation as well for fixed-base robots, for the problem of creating a stable transition from motion control to force control of a multi-joint manipulator. A mass-matrix weighted Lyapunov function is used to prove this stability, using the fact that the manipulator's kinetic energy decreases when an impact occurs. The transitioning controller used position measurement and used the first impact to obtain information on the actual location of the (fixed) impacting surface.

Brogliato and Orhant [7] have considered a one degree of freedom problem with some similarities to the one considered in this study. Relative to Brogliato and Orhant [7] and Pagilla and Yu [8], novelties of the present study include: (i) a lack of position measurement in the present study, (ii) the imposition of an acceleration (or force) bound on the control input in the present study, (iii) and the inclusion of an analysis of the effects of neglected dynamics in the input acceleration (force). As mentioned earlier, there is no position measurement used in achieving the continuous contact condition, and a force limit on the control magnitude is imposed.

In section 2.2, the problem statement is presented. In section 2.3, it is proved that the proposed controller converges to contact-maintenance in finite time. Issues of neglected
acceleration dynamics are discussed in section 2.4. In section 2.5, numerical examples are presented. Finally the conclusions are made in section 2.6.

2.2 Problem Statement

A plant with an acceleration input $u$ and unbounded impact acceleration $a_{impact}$:

$$\ddot{x} = a_{impact} + u \tag{1}$$

where an input bound $u_{\text{max}}$ exists:

$$-u_{\text{max}} \leq u \leq u_{\text{max}} \tag{2}$$

and where $a_{impact}$ produces an instantaneous change in the velocity $\dot{x}$ when an impact occurs at $x=0$ for $\dot{x} < 0$. The velocity change due to an impact is determined by a coefficient of restitution $\mu$, which may be time varying. Denoting an instant of impact by $t_i$,

$$\dot{x}(t_i^+) = -\mu \dot{x}(t_i^-), \quad x(t_i) = 0, \quad \mu \in [0, 1), \quad x(t_i^-) < 0 \tag{3}$$

where $\dot{x}(t_i^+)$ is the velocity right after impact and $\dot{x}(t_i^-)$ is that right before impact. The only feedback measurement is $\dot{x}$. The position $x$ is not measured. The following control is considered,

$$u = \text{sat}[-k(\dot{x}+c), A], \quad A > 0, \quad A \leq u_{\text{max}}, \quad c > 0, \quad k > 0 \tag{4}$$

where

$$\text{sat}(p, q) = \begin{cases} q, & \text{if } p > q \\ -q, & \text{if } p < -q \\ p, & \text{otherwise} \end{cases}, \quad q > 0 \tag{5}$$

The objective is to show that the above controller causes $x(t)$ to converge to zero in finite time, for any coefficient of restitution $\mu \in [0, 1)$.

2.3 Problem Solution
First, in Theorem 2.1, it is proved that \( x \to 0 \) as \( t \to \infty \). Then, Theorem 2.2 proves that this convergence occurs in finite time.

Theorem 2.1: The feedback control system defined by equations (1)-(5) is stable with \( x \to 0 \) as \( t \to \infty \), for all \( \mu \in [0,1) \).

Proof of Theorem 2.1: Here we will prove that the sequence of post-impact velocities \( \dot{x}(\bar{T}_i^+) \) converges to zero for all \( \mu \in [0,1) \).

Considering a general pair of adjacent impact times \( \bar{T}_i \) and \( \bar{T}_{i+1} \), there are three possible cases for the saturation function in equation (4) for \( t \in [\bar{T}_i^-, \bar{T}_{i+1}^-] \), i.e., the time interval between impacts:

(i) \[ -k(\dot{x}(t)+c) \leq A, \, \forall t \in (\bar{T}_i, \bar{T}_{i+1}) \]  

(ii) \[ \exists T_i \in (\bar{T}_i, \bar{T}_{i+1}): \begin{cases} 
  -k(\dot{x}(t)+c) = A, \, \forall t \in (\bar{T}_i, T_i) \\
  -k(\dot{x}(t)+c) < A, \, \forall t \in (T_i, \bar{T}_{i+1}) 
\end{cases} \]  

(iii) \[ -k(\dot{x}(t)+c) = A, \, \forall t \in (\bar{T}_i, \bar{T}_{i+1}) \]  

First consider case (ii). Let

\[ v_0 \equiv \dot{x}(\bar{T}_i^+) > 0 \]  
\[ r \equiv \frac{v_0}{c} \]  
\[ a \equiv \frac{A}{kc} \]  

Then, \( T_i \) in equation (7) is obtained from equation (1) and the condition

\[ k(\dot{x}+c) = A \]  

For the time interval \( (\bar{T}_i^+, T_i) \),
where the initial time is temporarily redefined as $\tilde{t}_i = 0$, merely for convenience, or,

\[ \dot{x} = -\tilde{A}t + v_0 \]  
\[ x(0) = 0, \quad \dot{x}(0) = v_0 > 0 \]  

Combining equations (16) and (12),

\[ k \left[ -\tilde{A}T_1 + v_0 + c \right] = A \]  

or,

\[ T_1 = \frac{v_0}{\tilde{A}} + \frac{c}{\tilde{A}} - \frac{1}{k} \]  

or, using equations (10)-(11),

\[ T_i = \frac{r + 1 - a}{ak} \]  

and

\[ x(T_i) = \left[ r^2 - (a - 1)^2 \right] \frac{k c}{2a} \]  
\[ \dot{x}(T_i) = -c + ca \]  

From equation (20), it is clear that $T_i > 0$ exists if $a < r + 1$ and is valid ($x(T_i) > 0$) if $r^2 > (a - 1)^2$, or

\[ r > |a - 1| \iff \text{case (ii)} \]  

From equations (13)-(14) and (10),

\[ x(T_i) = -\frac{1}{2} \tilde{A}T_1^2 + r \tilde{c}T_1 \]
\[ x_1 \equiv -\frac{1}{2}AT_1^2 + rcT_1 \quad (25) \]

\[ v_1 \equiv -AT_1 + rc \quad (26) \]

Re-initializing time again, merely for convenience, at \( T_1 = 0 \), and considering equations (1) and (4) again prior to the next impact, the plant is:

\[ \ddot{x} = -k\dot{x} - kc \quad (27) \]

\[ x(0) = v_1 \quad (28) \]

\[ x(0) = x_1 \quad (29) \]

The solution to equations (27)-(29) is:

\[ x = -\left(\frac{1}{2}\right)c\left[-2a - a^2 - r^2 + 1 + 2a(kt) + 2a^2 e^{-kt}\right]/(ka) \quad (30) \]

\[ \dot{x} = c\left[ae^{-kt} - 1\right] \quad (31) \]

\[ \ddot{x} = -ace^{-kt} \quad (32) \]

where the definitions in equations (10)-(11) have been used.

Since the interest is in the velocity just before the next impact, the values of \( kt \), if any, that render \( x \) to zero in equation (30) are important. It is clear that the acceleration \( \ddot{x} \) (in equation (32)) is strictly negative. With \( x_i > 0 \) and \( v_i > 0 \) there is therefore one and only one positive value of \( kt \) that renders \( x = 0 \) in equation (30). For convenience, this root is denoted as \((kt)^*\).

When there is no switch from saturation to non saturation, it is either case (i) or case (iii), from equations (6) and (8), respectively. The case (iii) represents equations (13)-(14) and non existence of a switch to non saturation before impact. In equation (13), the energy \( Ax + \frac{1}{2}\dot{x}^2 \) is...
conserved. Thus, the velocity magnitude $|\dot{x}(t_i^+)|$ just after impact will be equal to the velocity magnitude $|\dot{x}(t_{i+1}^-)|$ just before the next impact. So, for case (iii),

$$|\dot{x}(t_{i+1}^-)| \leq \mu |\dot{x}(t_i^+)|, \forall i, \text{ case (iii), } \mu \in [0,1) \tag{33}$$

For case (i), the storage function $V \equiv kcx + \frac{1}{2} \dot{x}^2$ has a non positive derivative $\dot{V}$, with $\dot{V} = -k \dot{x}^2$. Thus, the velocity magnitude $|\dot{x}(t_i^+)|$ just after impact will be less than or equal to the velocity magnitude $|\dot{x}(t_{i+1}^-)|$ just before the next impact. So, for case (i),

$$|\dot{x}(t_{i+1}^-)| \leq \mu |\dot{x}(t_i^+)|, \forall i, \text{ case (i), } \mu \in [0,1) \tag{34}$$

For case (ii), by finding the root $(kt)^*$ numerically, $\dot{x}((kt)^*)/c \equiv |\dot{x}(t_{i+1}^-)|/c$ can be plotted for the relevant values of $a \equiv A/(kc)$ and $r \equiv v_0/c$, i.e., for $a > 0$, $r^2 > (a-1)^2$ and $r > 0$ (from equation (23)). Figure 1 shows such a plot of $|\dot{x}(t_{i+1}^-)|/c$ versus $r \equiv v_0/c$. And, in Figure 1, the dashed line is the line $\dot{x}(t_{i+1}^-)/c = -\dot{x}(t_i^+)/c$.

![Figure 1](image)

**Figure 1.** Plot of $\dot{x}(t_{i+1}^-)/c$ versus $r \equiv \dot{x}(t_i^+)/c$ for $a > 0$ and $r^2 > (a-1)^2$ and $r > 0$, case (ii).

From Figure 1, it is always,
Thus,
\[
\left| \dot{x}(\bar{t}_{i+1}^-) \right| / c \leq v_0 / c = \left| \dot{x}(\bar{t}_i^+) \right| / c, \quad \forall i, \text{ case (ii)}
\] (35)

Thus,
\[
\left| \dot{x}(\bar{t}_{i+1}^-) \right| \leq \mu \left| \dot{x}(\bar{t}_i^+) \right|, \quad \forall i, \text{ case (ii), } \mu \in [0,1)
\] (36)

Combining equations (33), (34), and (36),
\[
\left| \dot{x}(\bar{t}_{i+1}^-) \right| \leq \mu \left| \dot{x}(\bar{t}_i^+) \right|, \quad \forall i, \mu \in [0,1)
\] (37)

Thus, the sequence \( \left| \dot{x}(\bar{t}_i^-) \right| \) converges to zero as \( i \to \infty \), for all \( \mu \in [0,1) \). This completes the proof of Theorem 2.1.

Remark 2.1: It is somewhat unconventional to use a plot, such as Figure 1, as part of a proof. But, it can be difficult to find a closed form storage function for a mixed case such as case (ii).

Theorem 2.2: The convergence in Theorem 2.1 occurs in finite time, with \( \bar{t}_{i+1}^- - \bar{t}_i^+ \to 0 \) as \( i \to \infty \).

Proof of Theorem 2.2: If \( a \leq 1 \), i.e., \( A \leq kc \), then case (iii) is the mode in which the final asymptotic convergence occurs. If \( a > 1 \), then case (i) is the mode in which the final asymptotic convergence occurs. For case (iii), it is easily verified that,
\[
\bar{t}_{i+1}^- - \bar{t}_i^+ = \frac{2r}{k\alpha}, \quad \text{case (iii)}
\] (38)

For case (i), re-initializing time at \( \bar{t}_i^+ = 0 \) for convenience,
\[
x(t) = \frac{c + rc}{k} - ct - \frac{c + rc}{k} e^{-kt
\] (39)
whose Taylor series in \( t \) is:
\[
x(t) = rct - \frac{1}{2}(c + rc)kt^2 + O(t^3)
\] (40)
whose root \( t^* \) in \( x(t^*) = 0 \) is:
\[ t^* \approx \frac{2rc}{c+rc} \quad (41) \]

so that

\[ t^* \rightarrow \frac{2rc}{c+rc} \quad \text{as} \quad r \rightarrow 0 \quad (42) \]

So, using Theorem 2.1 (equation (37)),

\[ \exists \eta \in [0,1) \quad \text{and} \quad I > 0 : \quad \forall i > I , \quad (\bar{t}_{j+1} - \bar{t}_i) \leq \eta(\bar{t}_{j} - \bar{t}_{j-1}) \quad (43) \]

Then, by the Ratio Test [11], the below limit exists and is finite:

\[ \lim_{N \to \infty} \sum_{i=1}^{N} (\bar{t}_{j+1} - \bar{t}_i) < \infty \quad (44) \]

This completes the proof of Theorem 2.2.

2.4 Consideration of Neglected Acceleration Dynamics

If the time between consecutive impacts, \( \bar{t}_{j+1} - \bar{t}_i \) is large compared to the time constant of the acceleration dynamics, neglecting these dynamics still yields a good approximation. For case (ii) (from equation (0)), \( kT_i + (kt)^* \) (\( T_i \) from equation (19)-(20)) is a function of only \( a \) and \( r \) and can be plotted versus the latter. And,

\[ \bar{t}_{j+1} - \bar{t}_i = \frac{kT_i + (kt)^*}{k} \quad (45) \]

In actual applications, the acceleration dynamics is going to be at least ten times faster than the \( \ddot{x} = -k\dot{x} \) dynamics. If the two-percent settling time of the acceleration dynamics is less than a tenth of \( \bar{t}_{j+1} - \bar{t}_i \), then it is reasonable to neglect the acceleration dynamics. For case (ii), this condition is:

\[ \frac{4}{10k} \leq \frac{1}{10} \left[ \frac{kT_i + (kt)^*}{k} \right] , \quad \text{case (ii)} \quad (46) \]

or,
\[ 4 \leq kT_i + (kt)^* \quad (47) \]

It can be easily verified that for \( a \) less than about \( \bar{\alpha} \approx 0.33 \), equation (47) is satisfied for all \( r \) (and not otherwise). Or,

\[ a < \bar{\alpha} \approx 0.33 \Leftrightarrow \text{equation (47), } \forall r > |a-1|, \text{ case (ii)} \quad (48) \]

For \( a < 1 \), it is easily seen from equations (6), (11), and \( v_0 > 0 \), that case (i) will not occur.

Consider case (iii). For case (iii), it can be shown that:

\[ k\left(\bar{T}_{i+1} - \bar{T}_i\right) = \frac{2r}{a} \quad (49) \]

The analogous to equation (46) is:

\[ \frac{4}{10k} \leq \left[ \frac{2r}{ak} \right], \text{ case (iii)} \quad (50) \]

or,

\[ r \geq 2a \quad (51) \]

From equation (23),

\[ a < 0.33 \Rightarrow \{ r \leq |a-1| \text{ necessary for case (iii)} \} \quad (52) \]

(See equation (48)). For \( a < 0.33 < 1/3 \) (see equation 48), \( r < 2a \Rightarrow r < |a-1| \). So, the condition for potentially significant acceleration dynamics reduces to,

\[ r < 2a, \text{ case (iii)} \quad (53) \]

So, finally, to assure a sufficiently small velocity level is reached before the acceleration dynamics become significant, consider this, letting \( \nu_{all} \) denote an allowable final velocity level:

\[ \left\{ \begin{aligned} 2a \leq \frac{\nu_{all}}{c}, & \quad a < 0.33 \\ \end{aligned} \right. \quad (54) \]

or,
\[ \{2ac \leq v_{\text{all}}, \ a < 0.33 \} \]  

If \( a = 1/20 \), for example, then \( \frac{1}{10} c \) can be assumed to be an upper bound on the final velocity level.

2.5 Numerical Examples

In this section numerical examples are presented for the plant and controller defined in section 2.2. The parameters for the first numerical example are: \( c = 1, \ a = 1/20, \ k = 1, \ x(0) = 0, \dot{x}(0) = 1, \ \mu = 0.9 \). The resulting position versus time history is shown in Figure 2.

![Figure 2. Position (x) versus time, \( a = 1/20 \).](image)

The second numerical example is the same as the first except that \( a \) is changed from 1/20 to 1.5. The resulting position history is shown in Figure 3.

![Figure 3. Position versus time, \( a = 1.5 \).](image)
The third numerical example is used to demonstrate that an unstable response can occur if
the acceleration dynamics are not fast enough. Here the equations (1)-(5) are modified to include
acceleration dynamics that have ten times the speed of \( \ddot{x} = -k \dot{x} \).

\[
\dot{x} = a_{\text{impact}} + w, \quad w \equiv a_c G(s), \quad G(s) \equiv \frac{-150s + \alpha^2}{(s + \alpha)^2}, \quad \alpha = 10k
\]

where

\[
a_c \equiv \text{sat}[-k(\dot{x} + c), A],
\]

The step response of the filter \( G(s) \) is shown in Figure 4, for \( \alpha = 100 \).

![Step Response](image)

Figure 4. Step response of neglected acceleration dynamics, \( G(s) \), \( \alpha = 100 \).

The following parameter values are considered in this numerical example: \( c = 1, \quad a = 10, \quad k = 10, \quad x(0) = 0.1, \quad \dot{x}(0) = 0.01, \quad \mu = 0.9, \quad \alpha = 100 \), and zero initial states of the filter \( G(s) \).

Figures 5-7 show the unstable response caused by the neglected acceleration dynamics.
Figure 5. $a=10$, illustration of instability for neglected acceleration dynamics.

Another view of the position response is shown in Figure 6.

Figure 6. $a=10$, illustration of instability for neglected acceleration dynamics.

The velocity is shown in Figure 7.

Figure 7. $a=10$, illustration of instability for neglected acceleration dynamics.
The time between impacts is initially about 0.16 seconds. And the acceleration dynamics' two-percent settling time is about 0.07 seconds. The value of $w$ in equation (56) never exceeded its bound $A$ in the simulation.

The fourth numerical example is used to show that the instability in the last example is removed by decreasing the value of $a$ as suggested in the previous section (e.g., equation (55)). The parameters are the same as in the last example except that $a=0.10$ instead of 10. The response is shown in Figures 8-9.

Figure 8. $a=0.1$, illustration of regained settling for reduced value of parameter $a$.

Figure 9. $a=0.1$, illustration of regained settling for reduced value of parameter $a$. 
The time between impacts is initially about 0.8 seconds. And the acceleration dynamics' two-percent settling time is still about 0.07 seconds. The value of $w$ (in equation (56)) never exceeded its bound $A$ in the simulation.

2.6 Conclusions

First the problem of a one degree of freedom, double integrator plant is considered, with an input bound and an impacting surface for which the coefficient of restitution may be time varying but is less than unity. A valid direction to the surface is known. The only feedback is on velocity. The controller's goal is to converge to contact maintenance. Then it is proved that the proposed simple saturating control law is stable for all positive parameter values. Later, the effects of neglected input dynamics are discussed and presented control parameter conditions for which these dynamics can be neglected while still achieving useful settling of the plant. Numerical examples demonstrated the former proved stabilities. Numerical examples also showed instabilities of the system when neglected input dynamics existed and the above mentioned control parameter conditions were not met.
CHAPTER 3

LITERATURE REVIEW OF QUADROTOR UAV

3.1 Definition of UAV

According to the Department of Defense dictionary, “an UAV is a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and can carry a lethal or non-lethal payload.” Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered as UAVs.

3.2 Background

UAVs have been famous for their ability to perform missions related to military applications. After the end of the Cold War, millions of dollars have been poured in research and development of UAVs by countries such as USA, Western Europe, Australia, Israel, China, and Russia [3]. Different types of UAVs for various military operations have been designed and put in to operation. Applications other than military such as volcano observation, environmental survey, infrastructure maintenance, atomic power plant surveillance, spraying pesticides in farms, law enforcement etc. have also been explored for UAVs. As more and more commercial applications are being considered for UAVs, affordability, reliability and safety of UAVs become more crucial.

Today, a large variety of UAVs are available depending upon the mission requirements. Though the large number of UAVs in use are fixed wing aerial vehicle, the ability of vertical take-off and landing (VTOL) vehicles can not be denied because of their higher maneuverability and capability of small area monitoring. VTOL vehicles can fly at low altitude, can hover, can provide detailed information about the area under surveillance and requires little ground support
in terms of launch and recovery equipments. Different configurations of VTOL vehicle including tail rotor helicopter, co-axial double rotor helicopter, ducted fans, tilt rotors, quadrotor etc. have been developed so far. Each of the above configurations has its own positives and negatives. Since this study is based on the quadrotor vehicle, the following section explains the background of quadrotor vehicle in detail.

3.3 Quadrotor

A quadrotor can be described as a vehicle with four fixed-pitch rotors located at the end of a cross frame. Figure 10 shows schematic of a quadrotor and explains the working of it. The front and rear rotors rotate in clockwise direction, while the right and left rotors rotate in counter clockwise direction to balance the torque produced by rotors on frame. All four rotors produce equal thrust in the upward direction if rotated at the same speed. The roll angle is controlled by varying the relative speed of left and right rotors, while keeping the total thrust produced by this pair of rotors same. Similarly, the pitch angle is controlled by varying the relative speed of front and back rotors. The yaw angle is controlled by varying the speed of right and left rotors relative to the speed of front and back rotors. Again the total thrust produced by all rotors is kept same. The altitude of the vehicle is varied by changing the speed of all rotors simultaneously. Thus, the quadrotor is controlled by only changing the speed of rotors without involving the complex mechanism, which makes the quadrotor more suitable for mini UAV applications. The four degree of freedom i.e. roll, pitch, yaw and thrust, can be decoupled from each other assuming a small deviation from hovering condition [12]. The quadrotor offers more payload capacity compare to conventional tail rotor helicopter. A quadrotor may be able to fly closer to an obstacle than conventional helicopter which has a large single rotor, without fear of a rotor strike.
However, because of quadrotor’s low damping rate, an attitude stability controller is required for stable flight.

Figure 10. Schematic diagram of quadrotor [14].

3.4 Previous Work Done On Quadrotor

The first quadrotor vehicle was built in 1907 by a French scientist and academician Charles Richet and Breguet brothers. They called it “Br’eguet-Richet Gyroplane No. 1”. The challenge was to build a machine which can lift itself along with a pilot off the ground using its own power. An 8-cylinder Antoinette IC engine (40hp) was used to drive four rotors. Each rotor had four blades. A simple belt and pulley mechanism was used to transmit the power from engine to rotors. The frame structure was made from steel tubes to support engine, four rotors and transmission mechanism. The total weight of the quadrotor was about 1124lb, including the frame (760lb) and the IC engine with fuel (364lb). The pilot weighted 150lb, making a net gross take-off weight of about 1274lb. The first flight with Gyroplane No. 1 was carried out at Douai,
France in 1907. The machine was tethered at the four corner of the frame. It has been reported that the Gyroplane No. 1 had lifted itself up to 5 ft [15]. The machine is shown in Figure 11.

![Figure 11. Bréguet-Richet Gyroplane No. 1 [15].](image1)

In 1920, Etienne Oemichen, built a quadrotor machine with eight additional rotors for control and propulsion. It is shown in Figure 12. Since the initial design was under powered, a hydrogen balloon was used to provide additional lift and stability to the machine. In 1924, Oemichen made a first successful flight without a hydrogen balloon. The machine was never used for any practical use [15].

![Figure 12. Quadrotor by Etienne Oemichen [15].](image2)
In 1922, Georges de Bothezat and Ivan Jerome successfully built a large quadrotor for the US Army. The machine was controlled by varying collective, differential collective and cyclic blade pitch. Also a set of four small rotors was used to help control the machine. The machine was called "Flying Octopus". It is shown in Figure 13. In 1922, they flew the machine successfully. But the project was dropped thereafter because of its unsatisfactory performance, high cost, and the increasing military interest in the gyroplanes at that time [15].

![Image of Flying Octopus](image)

Figure 13. “The Flying Octopus” by Georges de Bothezat and Ivan Jerome [15].

Since then the quadrotor configuration did not get much attention until early ‘80s. After that, many researchers have started considering the quadrotor configuration for mini UAV applications due to its simplicity, higher payload capacity and low cost.

The Draganflyer from www.rctoys.com is a very famous commercially available radio controlled mini quadrotor vehicle. It comes with an onboard attitude controller. Dragonflyer is relatively easy to fly compare to a conventional RC helicopter. It is shown in Figure 14. The frame of vehicle is made from carbon fiber tubes which are light weight and provide enough strength to the structure. It has three onboard piezoelectric gyros for self stabilization. Now days, many researchers are using Draganflyer as base vehicle for their research work.
The Quattrocopter is an impressive quadrotor micro air vehicle (MAV) designed by European Aeronautic Defense and Space Company (EADS). The Quattrocopter is about half a kilogram in weight and measures 65cm in size. It can fly for 20 minutes with 1 km of operating range and has 50% payload capacity to carry small spy camera and other sensors. It is the only commercial quadrotor UAV designed for industrial and defense applications. The onboard controller, called micro-avionics autopilot, includes six inertial sensors, GPS, air-data sensors and microcontroller. The Quattrocopter is shown in Figure 15.
Figure 16. Quattrocopter from EADS [16].

The X4 Flyer Mark II, shown in Figure 17, is designed and built at Australian National University, Canberra, Australia, to study the issues of maximum thrust and dynamic stability. The vehicle is designed for indoor applications.

Figure 17. X-4 Flyer Mark II [17].

The research group at Stanford University, The Stanford Testbed of Autonomous Rotorcraft for Multi Agent Control (STARMAC), is using a quadrotor as base vehicle to study the new multi agent algorithms to avoid collisions and obstacles. An onboard PD controller is
developed for inner loop attitude stability control. Two PIC microcontrollers have been used, each for motor control and communication purpose. Onboard sensors include an IMU, which gives all nine states of the system (roll, pitch, yaw, three angular rates and acceleration in X, Y, and Z), a differential capable GPS receiver and an ultrasonic sensor. Kalman filtering technique has been used to control the absolute position of the vehicle. A Bluetooth device has been used for wireless communication between the quadrotor and the ground station. The ground station includes a laptop running LabVIEW which interacts directly with vehicle and a computational cluster of up to four computers running Matlab to generate path trajectories for each flying vehicle. Outdoor flight tests have been carried out to demonstrate the performance of control algorithm. A picture is shown in Figure 18.

![STARMAC](image_url)

**Figure 18. STARMAC [18].**

Scott D. Hanford, et al, [13] have tried to build a low cost testbed for a quadrotor. Lightweight and low cost analog rate gyros, MEMS based accelerometer and PIC microcontroller are used. A proportional and integral (PI) controller is designed for inner-loop stability control. It is tested on a single degree of freedom test stand shown in Figure 19. Finally, the whole assembly of quadrotor is mounted on a Whitman training stand which gives the vehicle a limited degree of
freedom in yaw, pitch and roll while preventing it from crashing. Figure 20 shows the quadrotor mounted on a Whitman training stand. The successful flight was not achieved due to high frequency noise generated through the flexibility in vehicle structure.

Considerable amount of research work has been done in developing various control methodologies for quadrotors. Samir Bouabdallah, et al, [19] have compared the stability performance of quadrotor for proportional-integral-derivative (PID and linear quadratic (LQ_
techniques. Ming Chen, et al, [20] have derived a combined model based predictive controller (MBPC) and 2 degree of freedom (DOF) $H_\infty$ controller for a quadrotor UAV.

Erdinc Altu, et al, [21] have developed two different position controllers for quadrotor, one is based on linearization feedback controller concept and the other is the backstepping controller. The visual feedback system has been used to measure the pose of vehicle.

Interestingly, J. Dunfied, et al, [22] have developed a neural network based controller to hover a quadrotor vehicle. The research work includes generating training data while flying the vehicle manually, training the neural network using Matlab in PC, generating similar neural network controller in onboard Motorola MC68HC912DG128 microcontroller and set up a control architecture in the microcontroller to use the onboard neural network to control the vehicle. Two tilt sensors, one compass and three piezoelectric gyros are used as onboard sensors to provide training data and feedback to the controller. A two layer feed forward back propagation network, with log sigmoid transfer function, has been used. J. Dunfied, et al, [22] describes the potential problems in generating valid training data, processing speed of microcontroller and communication speed as the limitation for the sampling rate of sensors and command signals.

The research work done so far by various research groups around the world suggests that the quadrotor configuration is a better choice as a platform for UAV application compare to a tail rotor helicopter. Various attitude stability control schemes have been developed and tested for quadrotor configuration. A simple PD controller can offer enough stability to the vehicle to conduct the intended experiments for this thesis work. Additional payload capacity offered by quadrotor can be used to put more devices such as GPS and ultrasonic sensor onboard.
CHAPTER 4
BUILDING OF TESTBED

4.1 Base Vehicle

The objective of this research work is to demonstrate the capability of the rotorcraft vehicle to fly with protective shroud and stabilize by itself after a collision with obstacles around it. There are certain requirements that need to be met by the rotorcraft platform to be used for the experiments. The vehicle should offer the good amount of payload to accommodate the additional weight from shroud, gyros and onboard controller. Also, the vehicle should be such that, the protective shroud, designed to cover vehicle body and blade/s, should be of minimal weight and can be installed with great ease and without significant modifications in original vehicle configuration. Besides that, the vehicle should be cost effective, can be repaired with minimum efforts, time and cost, since experiments involve impact of vehicle with building wall.

With these requirements, a quadrotor configuration was a natural choice because of the advantages offered by it compared to the conventional tail rotor or double rotor helicopter. The working of quadrotor and its background is briefly discussed in chapter 3. Due to its inherent shape, it is easy to design and implement the protective shroud to cover all rotor blades. The design of vehicle and protective shroud is discussed in following section with detail.

4.2 Base Vehicle with Protective Shroud

Since, the goal of this thesis work does not require to design and build a rotorcraft from scratch, a commercially available Dragonflyer quadrotor from www.rc-toys.com was purchased and modified as per the requirement of the project, keeping the key combination of rotors, motors and battery same. Dragonflyer can carry a payload of 0.5lb. The brief introduction of Dragonflyer is already discussed in section 3.4 and is shown in Figure 14.
Many different designs for protective shroud have been investigated. The primary design requirements were: the shroud should cover all four rotors, have enough strength to bear an impact with wall at 5mph, produce minimum vibration while in flight and have minimum weight. While it was almost difficult to satisfy all of the above requirements, since many of them contradict with each other, a trade of between these parameters was the only solution. Figure 21 shows the modified Dragonflyer with protective shroud.

![Figure 21. Modified Dragonflyer with protective shroud.](image)

The major change is the removal of onboard controller circuit and its mounting accessory. Instead, carbon fiber tubes and plastic joints are used at the center of frame to support an inertial measurement unit at the top and custom made control circuit at the bottom. Battery is places at the center to keep the center of gravity at the center of frame. The protective shroud is just the frame of light weight, high strength carbon fiber tubes joined by plastic L and cross joints. The resulting shroud is very light weight, under the payload capacity of original vehicle, but very flexible.
4.3 System Configuration

This section explains the overall system configuration and its individual components in detail. Figure 22 shows the schematic of overall system configuration. The whole system can be divided between onboard system and ground station. Onboard system includes an inertial measurement unit, pulse width modulation (PWM) co-processor, motor driving circuit and Lithium polymer battery pack. Ground station includes Pentium IV PC running LabVIEW 7.1, PCI6024A NI DAQ card and joystick. Two RS232 buses are used for communication between onboard system and ground station.

4.3.1 Inertial Measurement Unit

An inertial measurement unit (IMU), 3DM-GX1 from Microstrain Inc is used to measure the states of system. It consists of three angular rate gyros, three orthogonal DC accelerometers, three orthogonal magnetometers, multiplexer, 16 bit A/D converter, and an embedded
microcontroller. Three gyros track the dynamic orientation, while DC accelerometers and magnetometers measure the static orientation. The microcontroller combines static and dynamic measurements from all nine sensors and filter through an algorithm in real time. The real time stabilized data are useful especially when dealing with vibratory environment. 3DM-GX1 can output pitch, roll, yaw, angular rates and axial accelerations in X, Y, Z directions. 3DM-GX1 is small in size, light weight and accurate enough. It provides orientation data in Euler, quaternion and matrix format through standard RS232.

The 3DM-GX1 is placed on top of the shroud frame with black plastic cover to reduce the effect of electro-magnetic field generated by motors running at very high speed. It is directly connected to PC through standard RS232 port. The data from 3DM-GX1 are read and used for attitude stability controller programmed in LabVIEW 7.1. The gyro stabilized data are found to be sensitive to the vibration and affect the overall stability performance of vehicle.

Figure 23. 3DM-GX1 inertial measurement unit [23].
4.3.2 PWM Co-processor and Motor Driving Circuit

As stated earlier, a Quadrotor can be controlled by just changing the speed of rotors. Since, four small 12V DC motors are used to power the rotors; PWM method is used to change the speed of motors. PWM signals can be generated by different methods. Microcontrollers are widely used to generate such signals. Many microcontrollers are capable of generating multiple PWM signals for controlling more than one peripheral without affecting the total cycle time of program running on it. A similar approach is used here. Since it is required to generate four independent PWM signals to control speed of four 12V DC motors of Quadrotor, an off-the-shelf PWM co-processor called PAK-Vc from www.awce.com, is used for this application. PAK-Vc PWM co-processor is capable of generating 8 PWM signals simultaneously, making the main processor computational power free for doing other calculations such as acquiring sensor data and computation of control signal.

The duty cycle of each PWM channel can be controlled by sending a command value followed by channel address via TTL level RS232 protocol at 9600 or 2400 baud rate. It requires minimum connections (two in this application) to connect to the host PC. It can also connect multiple devices to the same port with one additional pin per device. To operate PAK-Vc, it must be connected to a regulated supply of 5V DC and a clock element. A 50MHz ceramic resonator
is used to clock the chip. Figure 25 shows the pin diagram of PAK-Vc PWM co-processor with required connections.

![Figure 25. PAK-Vc PWM co-processor and its circuit connection.](image)

Since the PAK-Vc does not support the standard RS232 signal, a MAX232CPE IC is used to convert the standard RS232 signal from host PC to TTL level signal, compatible to PAK-Vc. Figure 26-27 show the connections of MAX232CPE IC with host PC. IC 7805 is used to get regulated 5V DC which is required to power MAX232CPE and PAK-Vc ICs.

The low current 5V PWM signal from PAK-Vc is not sufficient to drive 12V DC motor at high speed. An amplifying circuit is required to drive 12V DC motors. Four IRLZ34 FETs are used for this purpose. An amplifying circuit is shown in Figure 28.
Figure 26. MAX232CPE IC pin diagram [24].

Figure 27. MAX232CPE IC circuit connections [25].
Figure 28. DC motor driving circuit (R1=56K Ohm, R2=43K Ohm and D1=diode).

Figure 29. PWM co-processor and motor driving circuit.
4.3.3 PD Attitude Stability Controller

The most important issue while designing an UAV is the stability of the vehicle. An attitude stability controller is required to have stable flight, since the dynamic of quadrotor has low damping rate [6]. The additional disturbances from flexible plastic joints, carbon fiber tubes and impact with wall affect the overall stability of the vehicle. The stability controller keeps the vehicle stable before, during and after an impact with wall. It makes flight easy and allows pilot to do other maneuvering without taking care of vehicle stability. The controller also allows the vehicle to fly while maintaining continuous contact with the wall. This capability adds a great advantage to the vehicle to continue flying even after a small hit with the wall, where other vehicles fail and turn hostile. Assuming only small angular deviation in roll and pitch a classical Proportional Derivative (PD) controller has been designed to address attitude stability problem. Figure 30 shows schematic of close loop feedback control system. The flowchart of PD controller is shown in Figure 31. In addition to stabilizing pitch and roll angles, maintaining the yaw angle is also critical at the moment of collision with wall. A yaw-holding controller should not saturate the control input signal at the time of collision which leads to an abrupt change in yaw angle. The Yaw-holding control is almost a PD control except that the proportional term is purposely saturated to prevent it from causing saturation of the roll/pitch PD controls. The PD controller is programmed in LabVIEW 7.1. Figure 32 and 33 show the block diagram and front panel of Main Program.vi, respectively. Many other custom sub VIs are developed to make the Main Program.vi small and easy to handle. The block diagrams of sub VIs are shown in Appendix.
Figure 30. Schematic of PD controller.

Figure 31. Flowchart of PD attitude stability controller.
Figure 32. LabVIEW block diagram of “main program.VI”.

Figure 33. LabVIEW front panel of “main program.VI”.
CHAPTER 5

EXPERIMENTAL RESULTS, CONCLUSION AND FUTURE WORK

5.1 Single Axis, Double Rotor Test System Results

As stated earlier, the stability of UAV during flight depends on the performance of attitude stability controller. Since the main goal is to test the ability of quadrotor to bear the impact with building wall and to continue hovering thereafter, the attitude controller should be capable of maintaining roll and pitch angle close to hovering conditions in the presence of impact disturbance and sensor noise.

To test the performance of attitude controller, a single axis, two rotor test system has been developed. Two motor/rotor assemblies are mounted on each side of carbon fiber tube pivoted at the middle. A low friction ball bearing is used to provide smooth rotational movement in single axis. The electronics and software used for the single axis test system are identical to those to be used in actual flight test. The single axis test system is shown in Figure 34. During the test, voltage applied to the motors is maintained at the level enough to lift the actual vehicle at approximately 2ft. The objective is to maintain the hovering attitude (in this case, maintaining roll angle close to zero) in the presence of rotor vibrations, sensor noise and disturbance applied manually to imitate the disturbance due to the impact with building wall in actual flight test. Roll angle and angular rate in X-axis are samples at approximately 55Hz and recorded online. The experiments are conducted for approximately 21 seconds. Figures 35-36 show roll angle and angular rate respectively. When all gains are set to zero, roll angle settled down at -15degrees because of unbalanced weight with respect to pivot. After setting the gains to the predefined values, the two rotor system balanced itself while maintaining the steady state value between 0 to 5 degrees. High frequency noise can be clearly seen in both signals. The steady state error can be
explained as the result of small proportional gain (1.9) and bearing friction. Similarly, the small steady state variation in output signal (Roll Angle) can be explained as the result of high frequency noise in angular rate signal and high derivative gain (26). The vibrations, caused by flexible rotors, backlash in gear assembly and flexibility in carbon tubes and plastic joints, are considered to be the major source of high frequency noise in angular rate signal and main reason behind the poor steady state performance. To replicate the effect of impact in actual flight test, two external disturbances are applied manually between 7 to 8 second and 14 to 15 second. From Roll Angle signal, the capability of PD controller to handle the disturbance can be clearly seen. The issue of steady state error can be tackled in actual flight test by tuning the control signal through LabVIEW program. Three blue tuning bars on front panel of Main Program.vi can be clearly seen in Figure 33. The test results with single axis two rotor systems may differ from the results from actual flight test, but can be used as guideline while setting proportional and derivative gains of attitude controller. The cross coupling in vehicle dynamics, absence of vibrations from protective shroud, etc. may degrade the stability performance of vehicle in actual flight test.

Figure 34. Single axis test system for testing attitude controller performance.
Figure 35. Roll angle.

Figure 36. Angular rate in X-axis.
5.2 Flight Tests Results

Many test flights have been carried out for the quadrotor vehicle with protective shroud. Various scenarios, likely to be handled by rotorcraft UAVs flying at low altitude during tactical missions, have been imitated and the performance of the stability controller has been studied.

5.2.1 Flight Test Scenario-1

Preliminary results using the preliminary protective shroud in Figure 37 are shown in Figures 38-39. Figure 38-39 demonstrate the ability of the vehicle to continue successful flight following a collision with a brick wall at 2.3 mph. The complete set of frames (not shown here) of the video are 0.07 seconds apart; this allows us to estimate the velocity at which the vehicle is hitting the wall. This preliminary protective shroud does not allow a vehicle-to-vehicle collision.

A standard 4 channel joystick is used to provide user inputs to the vehicle. Pilot control is required to give initial velocity to the vehicle towards the wall, to drive the vehicle away from the wall following a collision and to maintain the hovering position between two brick walls.

In Figure 37, the wires are present simply for convenience. The wires provide power from 12v car battery and facilitate the communication between ground station and onboard controller. The Lithium Polymer flight battery can provide total flight time of 5 minutes at the thrust level required to hover the vehicle with protective shroud at approximately 2ft. It takes 2 hours to fully charge the Lithium Polymer flight battery. Short flight time and long charging time force author to use a 12v car battery which gives enough flight time to carry out flight tests without recharging the battery. The car battery does not provide extra r.p.m. to the rotors than the onboard flight battery’s rpm capacity. To replicate the real test flight conditions, the onboard flight battery is placed on the vehicle in Figures 38-39 just as it is in Figure 37. It is not providing power to the vehicle in any flight tests scenarios.
Figure 37. Preliminary protective shroud.
Figure 38. Flight test scenario-1 (Frames at 0.2sec intervals, continued in Figure 39).
5.2.2 Flight Test Scenario-2

It is required to fly a rotorcraft UAV very next to the other flying UAVs in tight space conditions. In such scenario, the shroud should protect the rotorcraft blades from vehicle-to-vehicle collisions. To allow inter-vehicle collisions, the shroud from Figure 37 is modified as shown in Figure 40.

![Figure 40. Modified shroud to allow inter-vehicle collisions.](image)

It is easily verified that the modified shroud allows rotor contact from a neighbor vehicle only when the two vehicles are tipped by almost 45 degrees relative to each other, as shown in Figure 41, in which contact between a shroud corner and the blue rotor occurs. This sole means of possible rotor contact can also be eradicated by adding four short cross-bars on the top of the shroud. For this test scenario, two Lithium batteries are used in series for extra thrust.
Preliminary results using the shroud of Figure 40 are given in Figures 42 and 43. Figures 42-43 demonstrate the vehicle colliding with the wall at 2.8mph and then continuing to fly in a stable manner after the collision.

Figure 41. Illustration of possible rotor contact.

Figure 42. Flight test scenario-2 (Frames at 0.2sec intervals, continued in Figure 43).
Figure 43. Flight test scenario-2 (Frames at 0.8sec intervals, continued from Figure 42).
5.2.3 Flight Test Scenario-3

Figure 44 shows a successful inter-vehicle collision in which the two faces of the vehicles collide. The relative velocity between the two vehicles was estimated to be about 3.5mph in Figure 44. Figure 45 shows a successful inter-vehicle collision in which the corner-edge of the first vehicle collides with the face of the second vehicle. In Figure 45, the relative impact velocity is estimated to be 2.7mph.

Figure 44. Flight test scenario-3 (Face-to-Face inter-vehicle collision, frames at 0.2sec intervals).

Figure 45. Flight test scenario-3 (Face-to-Edge inter-vehicle collision, frames at 0.2sec intervals).
5.2.4 Flight Test Scenario-4

To test the performance of roll/pitch/yaw holding PD controller, a collision in which the vehicle face heading into the corner of a building, is performed. Figure 46 shows a successful collision. The collision velocity is estimated to be about 2mph. Subsequent successful vehicle hovering is shown in Figure 47.

Figure 46. Flight test scenario-4 (Frames at 0.2sec intervals, continued in Figure 47).
5.2.5 Flight Test Scenario-5

Similar to the previous test scenario, a successful 2mph collision of the vehicle’s corner edge with the face of a brick wall is carried out. Figure 48 illustrates a successful collision. The long vehicle hovering after a collision is shown in Figure 49.
Figure 48. Flight test scenario-5 (Frames at 0.2sec intervals, continued in Figure 49).
5.3 Conclusions

A quadrotor UAV has been built by modifying the existing Dragonflyer vehicle. A protective shroud has been designed and implemented on the modified base vehicle. It has been
tested for collisions up to 2.8mph speed with the brick wall. The collisions have caused little or no damage to the protective shroud and rotors.

The onboard electronics has been designed and successfully tested on a single axis, double rotor testbed system. The suitable values of PD controller gains have been obtained through trial and error method. The experimental results validate the capability of the PD attitude controller to keep the vehicle stable before, during and after the collision. After performing the flight tests in various scenarios, it has been observed that successful collisions between vehicle and brick wall followed by a stable hovering of vehicle have been achieved.

5.4 Future Work

The following recommendations are made for future studies:

- A good mathematical model should be derived and the stability of PD controller should be analyzed using a proper mathematical approach.
- The sources of high frequency vibrations e.g. flexible rotors, should be identified and the level of vibration should be reduced by using better alternatives e.g. carbon fiber rotors.
- Similar study can be done with a close loop altitude stability controller, employed along with the present close loop PD attitude stability controller.
- This study can be extended to the development of a fully autonomous quadrotor UAV with protective shroud. The autonomy can be achieved by addition of a GPS navigation system, wireless communication channel between onboard controller and ground station, digital camera and a close loop altitude controller.
LIST OF REFERENCES
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APPENDIX

BLOCK DIAGRAMS OF LABVIEW SUBVIS USED IN MAIN PROGRAM.VI

Block Diagram of “Send 3DM-G Data Request Command.VI”

Block Diagram of “Convert Control Signal.VI”
APPENDIX (continued)

Block Diagram of “Initialize Serial Port.VI”

Block Diagram of “PD Controller.VI”
APPENDIX (continued)

Block Diagram of “Gyro Data Calculation.VI”

Block Diagram of “Get Record From Serial Port.VI”
APPENDIX (continued)

Block Diagram of “Convert Serial Record to Integer Array.VI”