# Design and Development of Unmanned Tilt T-Tri Rotor Aerial Vehicle

K. Senthil Kumar, Mohammad Rasheed, and T.Anand

***Abstract*—**Helicopter offers the capability of hover, slow forward movement, vertical take-off and landing (VTOL) while a conventional airplane has the performance of fast forward movement, long range and superior endurance. The aim is to simulate and analyze the dynamic motion of tilt T-tri rotor UAV's configuration that combines the advantages of both rotary wing and fixed wing vehicle. The dynamic response of vehicle using force and moment equation in vertical flight, horizontal flight and also the most important of all, transitional mode transition from vertical to horizontal flight has been analyzed in 3 degrees of freedom. The response of the UAV during transition from vertical flight into horizontal flight in the longitudinal plane has been explained using MATLAB programs. Transition period response under constant thrust and constant altitude condition of the dynamics is analyzed separately. Extensive simulation results are obtained to validate the effective time of transition.

***Keywords*—**Tri rotor, Tilt T-tri rotor UAV, Transitional mode, UAV, VTOL.

## I. INTRODUCTION

THE development of the Tilt Rotor Micro Air Vehicle in the market has shown a great improvement in terms of its capability to do vertical take-off and landing and to cruise around in air within a certain area. It is relatively small and light, which means that it can do more missions, particularly in missions that involves tight confined spaces, in urban areas etc. On top of that, this enables the air vehicle not to use runway for its take-off and landing as discussed in [1]. In this paper, focus will be on vertical flight, cruising and also the transition from vertical flight to horizontal flight. Transition is the intermediate moment factor from hover to cruise. This special step is the most crucial because a UAV that is design with both hover and cruise can never cruise from hover if the transition fails. So to ensure that the UAV are able to hover and then cruise, the transition moment must be looked into carefully as it involves a totally different picture and involves much consideration such as velocity, thrust, gimbal angle and pitching requirements.

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All these happen differently at different gimbal angle. The gimbal angle here is the angle at which the motor makes with the UAV (airframe's) in the horizontal direction. To visualize the simulate moment of hover, transition and cruise, A mathematical model is required. With the mathematical model and the necessary parameters only then it can be translated into coding by using software called MATLAB. With that, plots and graphs for the various moments and gimbal angles can be generated and analyzed.

The main difference between the rotor air vehicle and fixed wing air vehicle is the source of lift. For fixed wing, the source of lift comes from the fixed airfoil surface while the rotorcraft derives its lift from the rotating motion of its rotor as mention in [3].

## II. TRI ROTOR UAV

The control policy of the UAV will be that, during the hover mode to transition mode, there will be various motions effects on the platform. From the generic model, it is known that there will be two rotors at the wing tip and another rotor at the aft of the platform. Hence, during the hover and transition mode, there will be a vertical lift cause by the three rotors propelling at the same rate and power. During this time, a pitching motion will occur when there is a change in the angular velocity of the rotor at the aft of the platform. An increase in power will cause the platform to be in nose down position, while decrease in power will cause the platform to be in a nose up position, clearly mentioned in [2]. Also, roll motion is achieved by the front two motor speed control. Meaning that, when the left rotor angular velocity decreases, the UAV will bank in to the left and when the right rotor angular velocity decreases, the UAV will then bank into the right. The rotor at the aft of the motor will act as a stabilizer ensuring that during cruise flight, it stabilizes the whole air vehicle while other motions are taking place. Yaw is the complicated motion because it involves the coordination of all rotors and also the gimbal angle of either rotor at the wing tip. The two rotors at the wing are rotating in the opposite direction of each other, and this yaw forces created by each rotor on the wing, will cancel out each other and the third rotor will be located at the tail platform which creates unbalanced torque [5].

With this understanding, we will use equations to equate the motions that was mentioned before and turn it into a mathematical model which will be in a program call MATLAB, and henceforth, allowing us to see and analyze the generated graphs.

## III. Tilt Rotor UAVs

To do hover and efficient cruise in a single aircraft platform, it simply means that we require the use of tilt rotor as told in [7]. A tilt rotor in an aircraft uses a pair or more of powered motors that are mounted on rotating shafts that are located at the end of the aircraft wings. With the existence of the tilt rotor and also the wing, the aircraft will be capable of having a vertical takeoff such as the helicopter, and also, the speed and range of a conventional fixed-wing aircraft [3]. This tilt rotor does not involve the tilting of any wings. The only part that is tilted is the rotors which are located at the end of the wing.

The tilt rotor UAV has the maneuverability of a helicopter coupled with a speed of a fixed wing UAV. With the combination, it will then perform hovering and then cruise flight after transition of its rotor tilting mechanism. The tilt rotor, as the name implies, simply uses the propellers for lift during vertical flight and propulsion during horizontal flight. During vertical flight, the rotors are tilted vertically, and by using the propellers to propel and blow downwards, will cause the lift effect. This simply resembles the act of a helicopter. On the other hand, as the aircraft gains considerable altitude, the rotor will start to tilt and becomes perpendicular to the ground like Panther UAV [6]. In this mode, the propeller at the rotor will act as a turboprop and the wing will provide the necessary lift. With the combination of the efficiency of the wing and the rotor, it will then cause the aircraft to achieve its lift and speed. In this mode, the aircraft that initially act as a helicopter is now transform into a propeller aircraft. These alterations between vertical and horizontal flight is call the hover and transition mode [7].

## IV. Methodology

Tri-Rotor UAV is basically having three rotors to lift up the UAV in the vertical flight, and then performs transition into cruise flight. Therefore, certain mathematical model will be used to simulate its motion dynamics using MATLAB to see its graph and patterns and hence to understand and analyze it. Several assumptions are made such as wind effect is negligible, ideal flight etc.

### A. Vertical Flight

At the initial stage, the tri rotor UAV will be at rest on the ground. Given the three rotors with two at the end of both wings and the third at the aft of the UAV, the rotors will be in an upright position or at a gimbal angle of 90 degrees. With the thrust that each motor has, when combined, it must be more than the weight of the UAV itself in order for the UAV to lift off the ground.

In Figure 1, shows an illustration of how an aircraft usually flies. This applies to those conventional aircraft with fixed wing aircraft, be it commercial or military. However in this paper and especially in this part of the discussion, vertical lift is of the more concern subject. Hence, the 'T cos n' will be 0 because for a simple reason, there will be not forward flight.

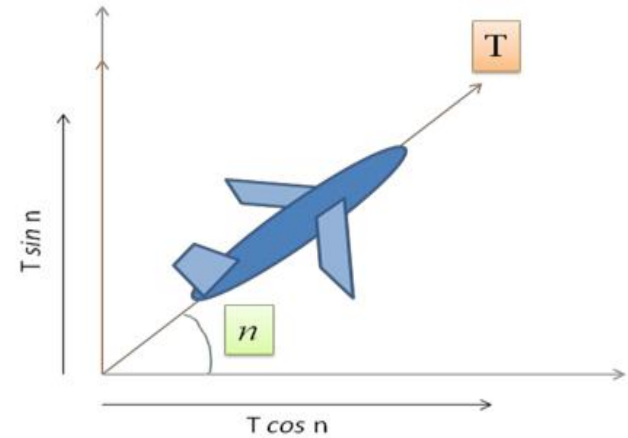


Fig. 1 Flight Trajectory

Simulation of the tri rotor UAV requires certain force and moment equations as in [5]. During this vertical flight for the tri rotor UAV, there will be no forward flight motion because as the name indicates, it is a straight up flight motion that is only possible by the combined maximum thrust of the rotors. Therefore, Equation (2) will be zero. As for Equation (2), it will be more of interest as it is the equation to designate the upward flight motion. The "*n*" here will then be 90° or 1.570796 radians. As for Equation (3), "$\dot{q}$" will be zero because in vertical flight, pitching is not something that is of concern of at the moment.

TABLE I
LIST OF SYMBOLS USED

| Symbol | Quantity |
|---|---|
| $\dot{u}$ | Forward flight Motion |
| $\dot{w}$ | Upward flight motion |
| $\dot{q}$ | Pitching moment |
| *m* | Mass |
| $C_L$ | Lift coefficient |
| $C_D$ | Drag coefficient |
| $C_M$ | Moment coefficient |
| *I* | Moment of inertia |
| *S* | Wing area |
| V1 | Forward Velocity |
| g | Earth gravity Constant |
| n | Gimbal angle |
| c | Chord |

Equation (1) and (2) are the force equation in horizontal and vertical axis respectively. Equation (3) is the moment equation in pitch axis. Since aircraft has a six degree of freedom, it should have three force equation and three moment equation. But here we considering only three equations combined with two force and one moment, because in this paper mainly concentrated in transition from vertical to cruise fly with assumptions of no side slip effect.

Force Equations:

$$\dot{u} = -qw + C_D \frac{1}{2}\frac{\rho v_1^2 s}{m} + \left(T_{max}\frac{\cos(n)}{m}\right) - g\sin\theta \qquad (1)$$

$$\dot{w} = -qu + C_L \frac{1}{2}\frac{\rho v_2^2 s}{m} + \left(T_{max}\frac{\sin(n)}{m}\right) - g\cos\theta \quad (2)$$

Moment Equation:

$$\dot{q} = C_M \frac{1}{2}\frac{\rho v_1^2 SC}{I} \quad (3)$$

*B. Straight and Level Flights*

During a flight, an aircraft have a total of four forces. These forces are the most fundamentals in every flight. The forces are Lift, Weight, Thrust and Drag. These factors are also known as the force balance in an aircraft. Hence, force balance of an aircraft allows the aircraft to fly in a straight and steady flight after they equalize all opposing forces and maintains it. Lift must be equal to weight so that the aircraft will not increase or decrease in altitude, the thrust must be equal to the drag so there will be no increase or decrease in its speed.

$$L = W \quad (4)$$

$$T = D \quad (5)$$

This phenomena is illustrates in [1]. When all of the forces are equal, then the aircraft will be in a straight and level flight. A change in any of these forces will cause a significant change in the other

$$L=½\rho V^2 SCL \quad (6)$$

$$D=½\rho V^2 SC_D \quad (7)$$

*C. Transition*

Transition is the most fundamental part of this project because, it is impossible for the UAV to alter it flight from vertical to horizontal. Transition steps are the intermediate points between vertical and horizontal flight. In transition, it is a bit complex because several factors have to be considered before transition occurs. It involves the combination of pitching, gimbal angle and the thrust during the transition period. It also has to be continuously executed at each transition point until the whole process completes or else error will sure to happen. It is basically involves the motion of the gimbal angle of the rotor, changing from vertical which is transition gradually from 90° and all the way down to 0° in 10° interval. At each gimbal angle, there will be different thrust, different velocity and also different lift and of course, different pitching moment.

$$\text{Forward thrust component} = T * \text{Cos}(n) \quad (8)$$

$$\text{Vertical Thrust component} = T * \text{Sin}(n) \quad (9)$$

$$\text{Velocity Achievable} = \sqrt{\frac{\text{Forward Thrust Component} \times 9.81}{0.5 \times \rho \times C_{\text{Total Drag}} \times S}} \quad (10)$$

$$\text{Lifts develop by wing, L (kg)} = \frac{1}{2}\frac{\rho V^2 s C_L}{9.81} \quad (11)$$

Equations (8) – (11) are the formulas used to calculate the horizontal, vertical thrust components, achieved forward velocity and the life developed by the wing due to forward motion.

## V. SIMULATION RESULTS

Computational simulation has been done in software called MATLAB. Results are displayed and discussed detail in this part. From the entire Figure 2 to Figure 28 below, it shows the different graphs for different gimbal angles. However, it addresses the same issue which is allowing the UAV to fly in trim condition at that particular gimbal angle without losing altitude. At gimbal angle of 80° which is shown by Figure 2, when the UAV is moving forward, the vertical component maintains its altitude for simple reason the vertical velocity is increasing because lift is increasing due to the increase in forward speed. The pitching moment then gradually decreases until both the horizontal component and vertical component goes to equilibrium.

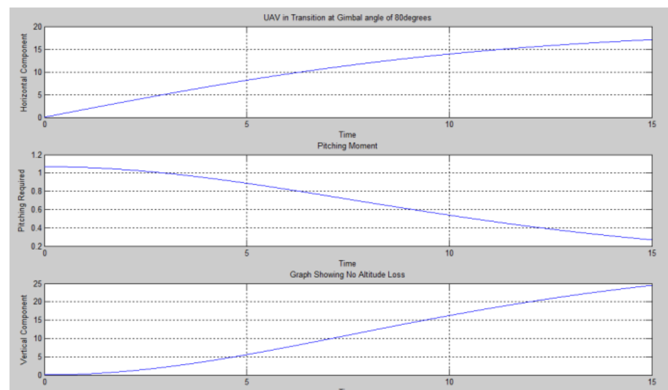


Fig. 2 Transition at Gimbal Angle of 80°

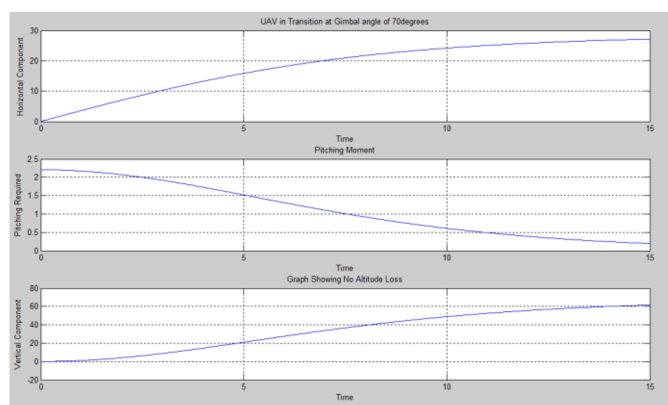


Fig. 3 Transition at Gimbal Angle of 70°

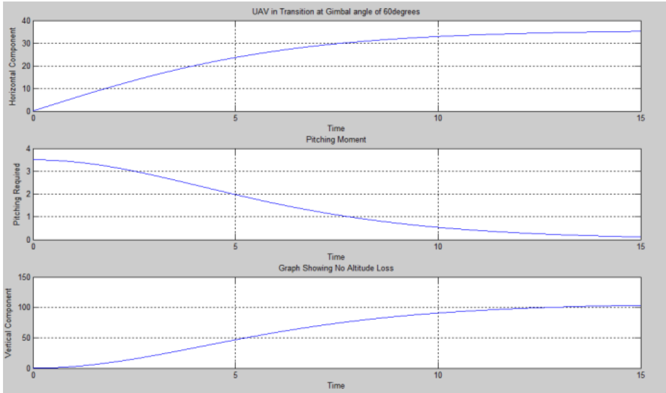

Fig. 4 Transition at Gimbal Angle of 60°

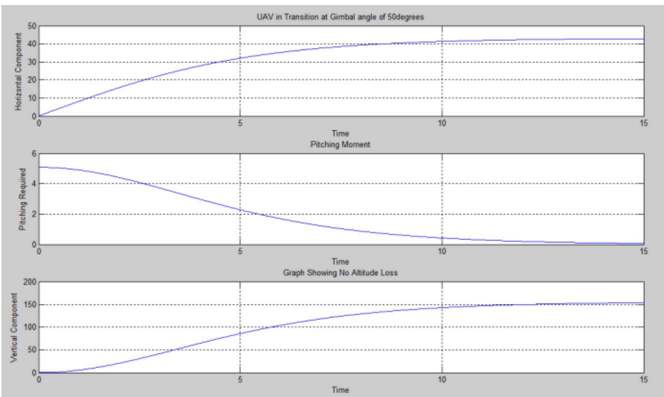

Fig. 5 Transition at Gimbal Angle of 50°

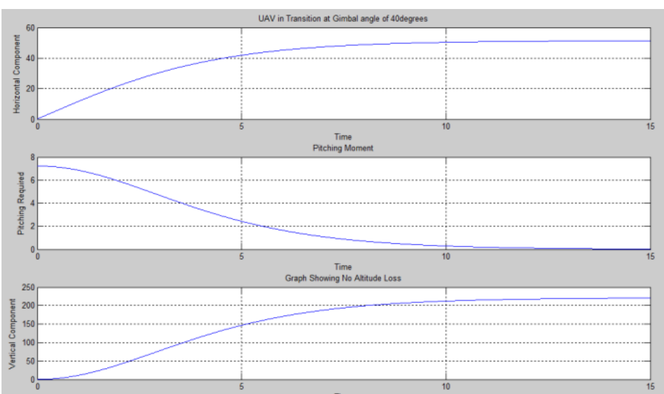

Fig. 6 Transition at Gimbal Angle of 40°

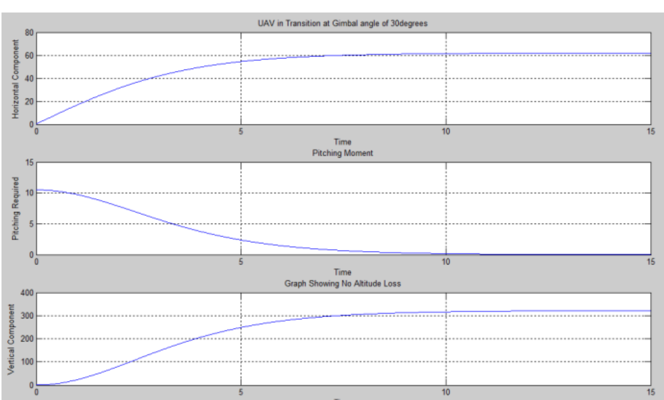

Fig. 7 Transition at Gimbal Angle of 30°

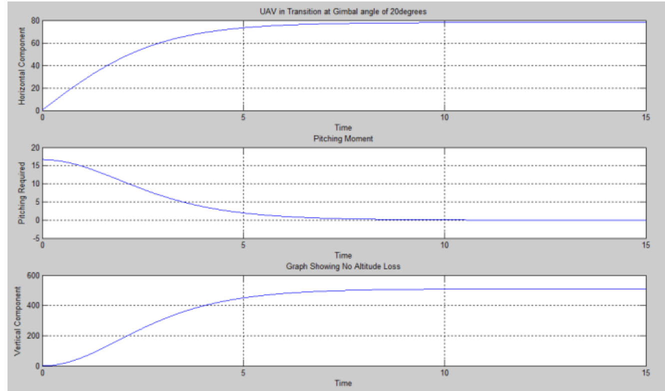

Fig. 8 Transition at Gimbal Angle of 20°

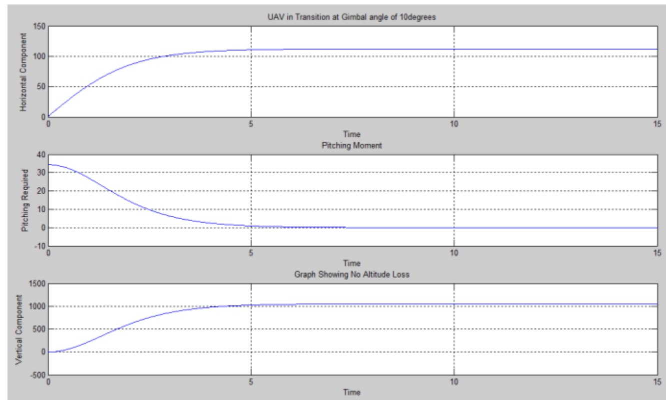

Fig. 9 Transition at Gimbal Angle of 10°

By absorbing figure (2) – (9), it is clear that the settling time is gradually decreases when the gimbal angle reduced. The time taken to trim for the 80$^o$ gimbal angle is very high than the 10$^o$ gimbal angle. By this we concluded that during transition, it is desirable to have the gimbal angle gradually decrease rather than a onetime change from 90° to 0°. If the latter situation happens, than the transition process will fail because there is a high chance that the UAV will drop in altitude at an instance and there will be not enough time for the UAV to pick up speed to maintain a trimmed flight when it reached gimbal angle 0°. Therefore, by gradually decreasing the gimbal angle and taking extra focus on the requirement of not having altitude lost will make the UAV to transit from vertical flight to horizontal flight in a smooth manner. This means force equilibrium during transition is desired.

Table (2) clearly explains, the change of total vertical force due to constant thrust in different gimbal angles. In this part of paper if we change the gimbal angle from 90$^o$ to 0$^o$ in the uniform interval 10$^o$, how the forward velocity will change, and due to the forward velocity how much lift will gain, are calculated and tabulated in table (2). Using equation (8)- (11), the forward thrust component due to tilting the motor, vertical thrust component , forward velocity achieved by tilting the motors and the amount of life developed by UAV's wing are calculated respectively.

TABLE II
TABULATION FOR CONSTANT THRUST TRANSITION

| Gimbal Angle | 80° | 70° | 60° | 50° | 40° | 30° | 20° | 10° |
|---|---|---|---|---|---|---|---|---|
| Weight(In kg) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Tmax(in kg) | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Air density (in kg/m$^3$) | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 |
| Lift co-efficient | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 |
| Drag Co-efficient | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 |
| Moment co-efficient | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 |
| Wing span(in m) | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 |
| Wing chord (in m) | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 |
| Wing area(in m$^2$) | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 |
| Gimbal angle (in radians) | 1.396263 | 1.22173 | 1.047198 | 0.872665 | 0.698132 | 0.523599 | 0.349066 | 0.174533 |
| Thrust available (in kg) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Forward thrust component(in kg) | 0.173648 | 0.34202 | 0.5 | 0.642788 | 0.766044 | 0.866025 | 0.939693 | 0.984808 |
| vertical thrust component(in kg) | 0.984808 | 0.939693 | 0.866025 | 0.766044 | 0.642788 | 0.5 | 0.34202 | 0.173648 |
| Velocity achievable (in m/s) | 6.279042 | 8.812196 | 10.65475 | 12.0807 | 13.18819 | 14.02244 | 14.60667 | 14.9532 |
| lift developed by wing(in kg) | 0.334886 | 0.659597 | 0.964267 | 1.239638 | 1.477343 | 1.670159 | 1.812229 | 1.899235 |
| total vertical force (in kg) | 1.319694 | 1.59929 | 1.830292 | 2.005682 | 2.12013 | 2.170159 | 2.154249 | 2.072883 |
| Excess vertical force(in kg) | 0.319694 | 0.59929 | 0.830292 | 1.005682 | 1.12013 | 1.170159 | 1.154249 | 1.072883 |

TABLE III
TABULATION FOR CONSTANT ALTITUDE TRANSITION

| Gimbal Angle | 80° | 70° | 60° | 50° | 40° | 30° | 20° | 10° |
|---|---|---|---|---|---|---|---|---|
| Weight(In kg) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Tmax(in kg) | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| Air density (in kg/m$^3$) | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 | 1.225 |
| Lift co-efficient | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 | 0.63 |
| Drag Co-efficient | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 | 0.0333 |
| Moment co-efficient | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 | -0.035 |
| Wing span(in m) | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 | 1.22 |
| Wing chord (in m) | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 | 0.177 |
| Wing area(in m$^2$) | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 | 0.21594 |
| Gimbal angle (in radians) | 1.396263 | 1.22173 | 1.047198 | 0.872665 | 0.698132 | 0.523599 | 0.349066 | 0.174533 |
| Thrust required for no altitude loss/gain (in kg) | 0.758 | 0.626 | 0.547 | 0.499 | 0.472 | 0.461 | 0.465 | 0.483 |
| Forward thrust component (in kg) | 0.131625 | 0.214105 | 0.2735 | 0.320751 | 0.361573 | 0.399238 | 0.436957 | 0.475662 |
| vertical thrust component (in kg) | 0.746484 | 0.588248 | 0.473716 | 0.382256 | 0.303396 | 0.2305 | 0.159039 | 0.083872 |
| Velocity achievable (in m/s) | 5.466735 | 6.972223 | 7.880195 | 8.533797 | 9.060586 | 9.520814 | 9.96042 | 10.3922 |
| lift developed by wing (in kg) | 0.253844 | 0.412908 | 0.527454 | 0.618579 | 0.697306 | 0.769944 | 0.842687 | 0.917331 |
| total vertical force (in kg) | 1.000328 | 1.001156 | 1.00117 | 1.000835 | 1.000702 | 1.000444 | 1.001726 | 1.001203 |
| Excess vertical force(in kg) | 0.000328 | 0.001156 | 0.00117 | 0.000835 | 0.000702 | 0.000444 | 0.001726 | 0.001203 |

By using table (2) concluded that by maintaining the thrust constant if we tilt the motor surely the UAV will gain the altitude respectively. So to maintain constant altitude without any change in height, we should change the motor speed correspondingly according to the gimbal angle. That has been calculate and tabulated in table (3).

## VI. CONCLUSION

A Tri Rotor UAV that is able to perform both hovering and enters into transition motion is something that is greatly desirable. It gives the extra edge in the aviation industry where this method can perhaps be adopted in the commercial industry and not only by hobbyist. Although in this paper, the idea of hovering is not been presented here, however the idea of having it to fly vertically and then performs transition, has been achieved. Rotation of gimbal angles for the UAV transition moment which is the most crucial part in tilt rotor uav's, that has been achieved. In the paper, it was clear that, the transition period, does not have any altitude loss, which is good because this is the requirement in transition.

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