CHAPTER 6

DESIGN OF BLENDING FUNCTION FOR LANDING PHASE FOR AN UNMANNED AIR VEHICLE

6.1 INTRODUCTION

The main aim of this research study is to achieve the autonomous landing of Unmanned Air Vehicle (UAV). The problem faced during the transition from glide path to flare is clearly addressed in the previous chapter. In this chapter, an attempt has been made to design and simulate the blending function for landing phase of an Unmanned Air Vehicle. A new concept termed as blending function which is used during the transition region is discussed and a possible solution is suggested. It mainly deals with glide path design, flare path design, design of blending function and interfacing the glide path and flare path with the blending function. During transition from glide slope to flare path, an UAV will tend to go to the unstable region. In a manned aircraft, the pilot controls the unstability and extreme severe oscillations that occurs during the change of phase from glide slope to flare which is impossible in UAV till now. A blending function has been formulated for use in UAV to overcome this unstability during transition. The proposed approach follows the standard practice to utilize MATLAB/SIMULINK and related toolboxes as the design platform.

6.2 BLENDING FUNCTION FOR SHAPE MODELING

Blending operations in shape modeling Pasko (1995) can generate smooth transitions between two or more surfaces. Blending is a natural
property of implicit surfaces, where the basic operation is an algebraic sum or difference between skeleton-based scalar fields. Users of computer-aided design systems also can apply blending operations for modeling fillets and chamfers. But in this application area, blending operations have different nature. New analytical formulations of blending operations can enhance function-based constructive shape modeling. Blending set operations can be applied in different ways to interactive design. These operations are usually smooth versions of set-theoretic operations on solids.

The major requirements for blending operations usually include

- Tangency of the blend surface with the initial surfaces
- Automatic clipping of unwanted parts of the blending surface
- Exact analytical or procedural definitions of blends instead of approximations
- Blending definition of the basic set-theoretic operations
- Intuitive control of the blend shape and position
- Support of blend for complex vertices where three or more surfaces are blended
- Support for blending a single selected edge, constant and variable radius blending.

Some of these requirements overlap or even contradict one another. Researchers WoodWark(1987) and Bloomenthal(1997) have proposed several methods for blending implicit surfaces and for blending versions of set-theoretic operations. However, the need exists in a continuous analytical description of set-theoretic operations with controllable blend shapes. The
proposed blending method in section 6.3 can have application in UAV landing design.

Figure 6.1 illustrates the bounded blending union operation of two rectangles with control points. In Figure 6.1 two control points rest on the corresponding boundaries of the rectangles. The expected bounded blend appears between the control points at the upper left part of the shape in Figure 6.2. However, the rectangles also blend in the lower right part of the shape, which can be unexpected or unwanted. The reason for this is that control points are not directly used for bounding the blend, but their coordinates are used in the functional formulation, which works for any other pair of points with the same function values. This example illustrates the global character of a blend with control points, which does not allow a designer to select a single vertex or an edge for blending.

Using a bounding solid let the user select a single feature (vertex or edge) of the constructive solid for blending. The corresponding pure set-theoretic operation should be replaced by the bounded blending operation. Figure 6.3 offers an example of the union of two rectangular solids. There is a blend in the area near a single vertex. The pure union operation, shown in
Figure 6.3 is replaced by the bounded blending union and the result is shown in Figure 6.4. The expected bounded blend appears inside the bounding disk in the upper left part of the shape in Figure 6.4. However, in comparison with Figure 6.2 no blending appears in the lower right part of the shape. This example illustrates the local character of the blending with a bounding solid.

![Figure 6.3 Blending Union at a Single Vertex](image1)

![Figure 6.4 The Pure Union Operation is replaced by the Blending Union](image2)

6.3 DESIGN OF BLENDING FUNCTION

The blending function is mixing of signals during the transition from glide path to flare path. This function is conceived in order to solve the problem of extreme oscillations and instability during the transition period. In the blending function, the gain of glide and flare path is varied according to variation in range. Hence, first it is decided to derive the range equation which is required for landing geometry.

6.3.1 Airport Selector Function

Calculation of the range is the first step in this design approach because in the glide slope geometry the control signal error depends on the
range to the runway threshold. The Airport Selector S-function was evaluated to determine whether the outputs from it were suitable for determining the range. The initial LLA and initial distance from the runway are output from the Airport Selector function and are suitable for finding the initial range and runway threshold LLA. In planning for lateral control, the Airport Selector S-function is modified to output the true heading of the runway.

6.3.2 Range Calculation

The simulator outputs LLA for the airplane at every step of simulation. Knowing the LLA of the runway threshold and the instantaneous LLA, the instantaneous range can be found. The instantaneous LLA can be subtracted from the threshold LLA to obtain the LLA difference. Assuming the earth is flat for small distances, this LLA difference represents a line in space that is found by the Pythagorean Theorem. For this simulation, the initial range chosen as 24,000 ft which is sufficiently small to consider the earth as flat.

The latitude and longitude are represented in degrees, where there are 60 minutes per degree and 60 seconds per minute and must be converted to feet so that they have the same units as altitude. The latitude conversion to feet is relatively constant from the equator to the poles and is approximated at all points as 6076 feet per minute. The longitude conversion to feet varies from the equator to the poles. This is because the lines of longitude become closer towards the poles. The circle created by intersecting a plane with the earth at some line of latitude will have a radius equal to the radius of the earth multiplied by the cosine of the latitude angle. The radius of this circle is used to calculate the circumference of the earth at that particular latitude. Regardless of the circumference of the circle, it still contains 360 degrees, thus a conversion factor can be found. The website www.earth.google.com
provides commonly used constants, conversion factors and measurements. The average radius of the earth is 36,522 feet. This then yields the conversion factor for longitude as 36,522*\cos(\text{latitude})\text{ feet per minute.}

Altitude is output from the simulation as feet above mean sea level. The runway altitude is output from the Airport Selector function and was subtracted from the instantaneous altitude to give the height above ground level (H). By the Pythagorean Theorem then, the range is given by

\[ R = \sqrt{(\text{latitude ft.})^2 + (\text{longitude ft.})^2 + (\text{altitude ft.})^2} \]  

(6.1)

where the latitude and longitude used in this calculation are the instantaneous latitude and longitude subtracted from the runway threshold latitude and longitude and converted to feet.

Subtracting the instantaneous LLA from the runway threshold LLA proved to be problematic for Simulink as regardless of the signs in the sum block, the range would only get larger. So, the initial range was found by using the initial ground distance and initial altitude output from Airport Selector. Then, the instantaneous LLA was subtracted from the initial LLA to find the change in range. After conversion to feet, this change was subtracted from the initial range to get the instantaneous range. This can present a problem if the aircraft does not establish the glide path quickly because the change in range can be greater than intended if the aircraft gets far off the desired path. However, with reasonably small errors in the flight path, this approximation works well.

Figure 6.5 illustrates the geometry to find out the instantaneous range of UAV which mainly depends upon the Latitude, Longitude and Altitude (LLA) of the UAV and the destination Runway.
Steps involved for LLA calculation are described as shown below:

(i) Known parameters are airport latitude, airport longitude, base elevation of the Runway and initial ground distance from which glide path starts.

(ii) Based on Range, height of aircraft above base elevation are calculated.

(iii) The aircraft LLA is calculated as

\[ \text{Gd}_{\text{ini}} \times \cos\left(\frac{\pi}{180} \times T_{\text{head}}\right) \times \frac{1}{6076 \times 60} + \text{Lat}_{\text{initial}} = \text{lat}_{\text{Threshold}} \]

\( Gd_{\text{ina}} \times \sin\left(\frac{\pi}{180} \times T_{\text{head}}\right) \times \frac{1}{6076 \times 60} + \text{Lon}_{\text{initial}} = \text{lon}_{\text{Threshold}} \)

\[ \text{Base elevation} = \text{alt}_{\text{Threshold}} \]

\[ \text{alt}_{\text{initial}} = h_{\text{initial}} + \text{Base elevation} \]

(iv) The Runway end LLA is calculated as
\[
\begin{align*}
\left[ \{ \text{Gd}_{\text{ini}} + \text{Runway length} \} \times \cos(\frac{\pi}{180} \times \text{T}_{\text{head}}) \times \frac{1}{6076 \times 60} \} \times \text{lat}_{\text{Initial}} \right] &= \text{lat}_{\text{Runwayend}} \\
\left[ \{ \text{Gd}_{\text{ini}} + \text{Runway length} \} \times \sin(\frac{\pi}{180} \times \text{T}_{\text{head}}) \times \frac{1}{6076 \times 60} \right] \times \cos(\frac{\pi}{180} \times \text{lat}_{\text{Initial}}) &= \text{lon}_{\text{Runwayend}}
\end{align*}
\]

\[\text{(6.6)}\]

Base elevation = \text{alt}_{\text{Runwayend}} \tag{6.7}

(v) Instantaneous Range and Height is calculated as

\[
\begin{align*}
\sqrt{\left[ \text{lat}_{\text{Threshold}} - \text{lat}_{\text{Initial}} \right] \times 6076 \times 60}^2 + \\
\sqrt{\left[ \text{lon}_{\text{Threshold}} - \text{lon}_{\text{Initial}} \right] \times 6076 \times 60 \times \cos(\frac{\pi}{180} \times \text{lat}_{\text{Initial}})}^2 + = \text{range}_{\text{Initial}} \\
\left[ \text{alt}_{\text{Threshold}} - \text{alt}_{\text{Initial}} \right]^2
\end{align*}
\]

\[\text{(6.9)}\]

\[
\begin{align*}
\text{range}_{\text{Initial}} - \text{range}_{\text{Delta}} &= \text{range}_{\text{Ins}} \\
\text{alt}_{\text{Ins}} - \text{Base elevation} &= \text{h}_{\text{Ins}}
\end{align*}
\]

\[\text{(6.10)}\quad \text{(6.11)}\]

The symbol and description of the various parameters used in the equations are given below:

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd_{ini}</td>
<td>Initial ground distance</td>
<td>T_{head}</td>
<td>True heading</td>
</tr>
<tr>
<td>lat_{Initial}</td>
<td>Initial latitude</td>
<td>lon_{Initial}</td>
<td>Initial longitude</td>
</tr>
<tr>
<td>alt_{Initial}</td>
<td>Initial altitude</td>
<td>lat_{Threshold}</td>
<td>Threshold latitude</td>
</tr>
<tr>
<td>lon_{Threshold}</td>
<td>Threshold longitude</td>
<td>alt_{Threshold}</td>
<td>Threshold altitude</td>
</tr>
</tbody>
</table>
6.3.3 Geometry of Blending Function

The proposed geometry of blending function is shown in Figure 6.6. In the blending function the gain of glide and flare path is varied according to variation in range. It is found that the glide path gain is decreasing and the flare path gain is increasing. By using a limiter, the upper limit of the gain is set to 1 and the lower limit is set to 0. At any point sum of the glide and flare path gains is 1. From range $R_1$ to $R_3$ the glide path alone will be present, the gain of the glide path is 1 and the flare path gain is 0. From $R_2$ to 0 only the flare path will be present, the glide path gain is 0 and the flare path gain is 1. In between $R_3$ and $R_2$ the blending function will occur and the gain will vary with glide path gain decreasing from 1 to 0 and flare path gain increasing from 0 to 1. The condition of the range is $(R_1 > R_3 > R_2 > 0)$.

![Figure 6.6 Geometry of Blending Function](image-url)
$R_1$ - The point from which glide path starts

$G_{g1}$ - Gain at which glide path starts

$R_2$ - The range at which glide path gain becomes zero

$R_3$ - The range at which flare path gain becomes zero

$G_{f1}$ - Flare path gain at $R_1$

The equation of straight line with coordinates $(x_1, y_1)$ and $(x_2, y_2)$ is given by:

$$y - y_1 = \frac{y_2 - y_1}{x_2 - x_1} (x - x_1) \tag{6.12}$$

such that the glide path gain equation with the coordinates $(R_1, G_{g1})$ and $(R_2, 0)$ as

$$G_g - G_{g1} = \frac{0 - G_{g1}}{R_2 - R_1} (R - R_1) \tag{6.13}$$

$$= \frac{-G_{g1}}{R_2 - R_1} (R - R_1) \tag{6.14}$$

$$= \frac{G_{g1}}{R_2 - R_1} (R_1 - R) \tag{6.15}$$

$$G_g = \frac{G_{g1}}{R_2 - R_1} (R_1 - R) + G_{g1} \tag{6.16}$$

Where $G_g$ - Glide path gain at every instant of Range R

And the flare path gain equation with the coordinates $(R_1, -G_{f1})$ and $(R_3, 0)$ as

$$G_f - G_{f1} = \frac{0 + G_{f1}}{R_3 - R_1} (R - R_3) \tag{6.17}$$

$$= \frac{G_{f1}}{R_3 - R_1} (R - R_3) \tag{6.18}$$
\[ G_f = \frac{G_f 1}{R_3 - R_1} (R - R_3) + G_f 1 \]  

(6.19)

Where \( G_f \) - flare path gain at every instant of Range \( R \)

In the region between range \( R_3 \) & \( R_2 \) the blending phenomenon will occur.

6.3.4 Implementation of Blending Function

The interfacing of blending function with the glide and flare path is shown in Figure 6.7.

![Figure 6.7 Interfacing of Blending Function with Glide and Flare Path](image)

The geometrical implementation of the blending equations using MATLAB / SIMULINK is shown in Figure 6.8.

![Figure 6.8 Blending Function](image)
Here $R_2 = 3000; R_3 = 5000; G = \frac{1}{R_3 - R_2}$

6.3.5 Sample Calculation

In this geometry, the Dallas Fort Worth International airport has been considered for the landing phase of UAV with the following known parameters: True heading of 180.3 deg, Base elevation of 607 ft, Latitude of 32.93483568652165 deg, Longitude of -97.0268825156042 deg and Initial ground distance of 24300 ft. These values are used to calculate initial range, instantaneous range, initial height and instantaneous height. Using steps (iii) to (v) the calculated values are found to be:

- Initial height = 1060.960 ft
- Initial altitude = 1667.96 ft
- Initial latitude = 33.00149046735776 deg
- Initial longitude = -97.0272315271941 deg
- Runway end altitude = base elevation = 607 ft
- Runway length = 6076 ft
- Runway end latitude = 32.91816924831753 deg
- Runway end longitude = -97.0267952483441 deg
- Initial range = 24323.1502096 ft
- Delta range = 6361 ft
- Instantaneous range = 24323.1502096 - 6361 = 17962 ft

With simulation run in MATLAB / SIMULINK environment for about 20 sec, it is observed that the simulated instantaneous range is equal to the calculated instantaneous range. Hence, it has been proved that the algorithm is more efficient and this has been verified with many more airports around the world.
6.4 SIMULATION RESULTS

6.4.1 Gain Variation with Range

Table 6.1 describes the gain variation with range starting from glide slope to touch down point. The simulation inputs namely latitude, longitude and altitude are given from the airport selector function and these values are used to calculate the range. The simulation results are shown in Figures 6.9-6.12. The range, glide multiplier gain and flare multiplier gain variation with time is shown. At the glide starting point, the range is around 23,000ft and by the time it reaches 86 sec, the range is 0 ft. This implies that landing has been accomplished.

Table 6.1 Gain Variation with Range

<table>
<thead>
<tr>
<th>Range(ft)</th>
<th>Glide path gain</th>
<th>Flare path gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>23000-5000</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5000-3000</td>
<td>1→0</td>
<td>0→1</td>
</tr>
<tr>
<td>3000-0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 6.10 shows the variation of the glide multiplier gain with range and it is found that from glide slope starting point i.e. 23,000 ft to 5000 ft the gain remains as 1, between 5000ft and 3000ft the gain gradually decreases from 1 to 0 and from 3000 ft to touch down point the gain decreases to 0.

Figure 6.9 shows that the flare multiplier gain varies in range from 0 to 1. The flare starting point is 5000ft and upto that point the gain is 0 and from 3000ft to till touch down the gain remains as 1. It means that in the flare path between 5000ft and 3000ft the gain is increasing from 0 to 1. It is observed from Figures 6.10 and 6.11 that between 5000ft and 3000ft the glide path gain is decreasing, the flare path gain is increasing and the blending phenomenon
is said to occur. From Figure 6.12 it is inferred that the summation of the
glide and flare path gains always remains 1.

6.4.2 Response of the Parameters Variation without Blending
Function

The responses of the various parameters without using blending
function are shown in Figures 6.13-6.19. The flare path starts at 3000ft, above
3000ft glide path alone will be present. In terms of time, upto 65 seconds only
glide path will be present and after 65 seconds the flare path alone will be present.

Figure 6.13 Response of Angle of Attack and Side slip

Figure 6.14 Response of Height and Decent rate

Figure 6.15 Response of Pitch, Roll and Yaw angles

Figure 6.16 Response of Pitch Rate, Yaw rate and Roll rate
Figure 6.17 Response of Aircraft Velocity in x, y and z Directions

Figure 6.18 Response of air Velocities in x,y and z Directions

Figure 6.19 Response of Elevator Command

From Figure 6.19 during transition from glide slope to flare path, UAV will go to sudden change warranting more deflection in the elevator
command which is not recommended during this transition. It might lead to landing accidents.

6.4.3 Response of the Parameters Variation with Blending Function

The responses of the various parameters with the blending function are shown in Figures 6.20-6.25. The blending phenomenon occurs in the range 5000ft to 3000ft, which means that between 5000ft and 3000ft the UAV will be in both glide path and flare path. Above the altitude of 5000ft (i.e. from 23000ft to 5000ft) UAV will be in the glide path and below the altitude of 3000ft (i.e. from 3000ft to touchdown) it will be in the flare path only. In terms of time, the blending phenomenon will occur between 59 and 65 seconds. During 0-59 seconds only the glide path will be present and after 65 seconds only the flare path will be present. From Figure 6.25 it is inferred that the airspeed autopilot is maintained during landing. At the end of the landing phase the Engine rpm, throttle position and thrust gets reduced.

![Figure 6.20](image1.png)  ![Figure 6.21](image2.png)

**Figure 6.20** Response of Angle of Attack and Sideslip  **Figure 6.21** Response of Height and Decent rate
Figure 6.22  Response of Pitch, Roll and Yaw Angles

Figure 6.23  Response of Pitch rate, Yaw rate and Roll rate

Figure 6.24 Response of Aircraft Velocities in x,y and z Directions

Figure 6.25  Response of Engine RPM, Throttle Position and Thrust
6.4.4 Comparison of Performance with and without Blending Function

Figures 6.27-6.34 show the comparison of angle of attack, sideslip, height, pitch rate, roll rate and yaw rate with and without blending function. The dotted lines indicate the parameter variation with blending function and thick line indicates the parameter variation without blending function. The parameters are compared with range variation.

In the range from 5000 ft to 3000 ft with time variation from 59 to 65 seconds, the angle of attack variation with and without blending function is as shown in Figure 6.27. On comparison, it is found that when the blending function is not included, the variation is large i.e. around 15% but when the blending function is included the variation is reduced to about 3%.
Figure 6.27  Response of Angle of Attack

Figure 6.28  Response of Decent rate

The decent rate shown in Figure 6.28 is smoother with the blending function than when compared to without the blending function. The smooth variation of decent rate means that when the oscillations get reduced, the steepness will also get reduced.
The comparison of heights shown in Figure 6.29 proves that the steepness of the aircraft is reduced. The exponential decay is found to be good while including blending function. If the steepness increases i.e. without blending function the force on the landing gear will also be increased. This may cause the landing gear failure and wear of tires which makes the landing of the aircraft difficult.
On comparing the pitch rate as shown in Figure 6.30. It is found that the variation and the oscillations are considerably more when the blending function is not included. The variations are reduced when the blending function is included.

![Figure 6.31 Response of Pitch](image)

The comparison of pitch is shown in Figure 6.31. It is found that the instant pitch is available by summing the pitch at the previous instant and the pitch rate at that instant. Hence, when the pitch rate varies the pitch will also vary automatically.

The variation of velocities with respect to x and z directions are shown in Figure 6.32 and Figure 6.33 respectively with and without the blending function. The blending function ensures reduced velocity in Z direction which will cause smooth contact of the wheels with surface on touch down.
The elevator command which is given to the elevator is shown in Figure 6.34 with and without blending function. The elevator deflection seems to be more when the blending function is not used, requiring more control power which might cause damage to control surface resulting in fatal accidents during landing. By using the blending function, the control power required to move the elevator is substantially reduced.
Thus by using blending function the oscillations are reduced and the control power is also considerably reduced as evident from the graph and ensures safe landing.

6.4.5 Comparison of the Performance Measures

Measures of performance are required to specify the desired landing conditions of aircraft. Basically, they require that the aircraft must land within the desired envelope of dispersions. Table 6.2 summarizes the blending performance measures.

Table 6.2 Performance Measures

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Without blending function</th>
<th>With blending function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Angle of attack</td>
<td>Variation is high</td>
<td>Variation is low</td>
</tr>
<tr>
<td>2. Decent rate</td>
<td>Sudden change</td>
<td>Smooth change</td>
</tr>
<tr>
<td>3. Height</td>
<td>Steepness is high</td>
<td>Steepness is low</td>
</tr>
<tr>
<td>4. Pitch rate</td>
<td>Variation is high</td>
<td>Variation is low</td>
</tr>
<tr>
<td>5. Pitch</td>
<td>Variation is high</td>
<td>Variation is low</td>
</tr>
<tr>
<td>Parameters</td>
<td>At the Glide slope begin (0sec)</td>
<td>At the start of blending function (59 sec)</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Angle of attack in degrees</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Sinkrate ft/s</td>
<td>20.8</td>
<td>14.71</td>
</tr>
<tr>
<td>Altitude in ft</td>
<td>1074</td>
<td>221</td>
</tr>
<tr>
<td>Pitch rate deg/s</td>
<td>3.7</td>
<td>-0.014</td>
</tr>
<tr>
<td>Pitch angle in deg</td>
<td>0.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Incremental Forward velocity (U) in ft/s</td>
<td>325</td>
<td>330</td>
</tr>
<tr>
<td>Incremental vertical velocity (w) in ft/s</td>
<td>12</td>
<td>35</td>
</tr>
<tr>
<td>Throttle</td>
<td>0.045</td>
<td>-0.06</td>
</tr>
<tr>
<td>Elevator command in deg</td>
<td>0.18</td>
<td>0.2696</td>
</tr>
<tr>
<td>Range in ft</td>
<td>24330</td>
<td>5000</td>
</tr>
</tbody>
</table>

The typical values of the parameters during the various landing phases are given in Table 6.3.

Table 6.3 Typical Values of Performance Measures
6.5 X-PLANE INTERFACE

Concentrating in aerial vehicles, X-Plane is used to verify/validate/refine controllers designed in MATLAB. Although there exist several simulators like Microsoft’s Flight Simulator and Flight Gear, X-Plane provides extremely accurate flight models and allows for external communication as well as airfoil design. It is accurate enough to be used to train pilots Meyer (2005). Unlike the Microsoft Flight Simulator and Flight Gear, however, X-Plane also allows for input and output from external sources. X-Plane provides future capabilities that Unmanned Aerial Vehicles will need, including navigation markers, changing weather conditions and air traffic control communication.

![Figure 6.35 X-plane Interface](image)

A key aspect of controller verification/validation/refinement is the actual communication and interface between the X-Plane and MATLAB/SIMULINK shown in Figure 6.35.

6.5.1 X-Plane UDP Communication

X-Plane Meyer (2005) uses UDP communication to send and receive data packets. This allows changes to be made to various values within X-Plane. The UDP protocol has advantages and disadvantages. UDP may be unreliable over a distant network connection because no error detection exists in the packets. On the other hand, UDP is extremely fast. X-Plane is able to
dump up to 50 frames per second across a local network. This has an important impact on controller functionality and simulation because they require sufficiently updated speed to operate correctly. X-Plane offers several parameters whose values may change, including control of the aircraft, failure introduction etc.,. In order to select the appropriate data items to export to SIMULINK, X-Plane provides an easy way to use checkbox interface. However, X-Plane is not open-source, hence it will be necessary to be familiar with the UDP documentation.

The path followed by the aircraft after interfacing X-Plane with Simulink Via UDP are shown in Figures 6.36 and 6.37. The aircraft landing sequence in X-Plane is shown in Figures 6.38-6.41.

| Figure 6.36 Desired and Actual Trajectory of UAV | Figure 6.37 Desired and Actual Trajectory of UAV with Waypoints |
The blending of signals at the switch of glide slope and flare control signals solved the problem of extreme oscillation and instability during the switch. In fact, graphically, the switch is almost unnoticeable. Figure 6.42 shows the response of the aircraft during the signal blend. Oscillation is not visible on this graph, but is very slightly visible in the graphics produced by X-Plane. Figure also shows the response of the aircraft during the flare. It flies an exponential path to touchdown approximately at 500 ft. from the runway threshold. It also touches down at a vertical velocity
of approximately four feet per second, which would be considered a good landing by any pilot.

Figure 6.42 Aircraft Response during Glide slope/Flare Switch and Touchdown

Because the flare path command is exponential, the aircraft tends to bounce if the elevator remains under control of the flare controller after main gear touchdown. To ensure the aircraft remains on the ground, the elevator is neutralized with a relay at an altitude above ground level equal to the height of the main gear (9 ft). At the same altitude, the throttle command is also neutralized and the brake command is changed from one to zero (zero to full braking) with a rate limiter to limit the brake application time to two seconds. The rate limiter on braking prevents gear failure due to over-braking upon touchdown.

Upon completion of a successful landing in ideal conditions, the system was tested at various airports to ensure adequate representation of landing geometry with reference to LLA coordinates. Successful landings indicated that the landing geometry definitions are in fact appropriate for use at any destination airport. The detailed descriptions of the nonlinear 6 DOF simulation architecture are given in the Appendix 2.
6.6 CASE STUDY - PERFORMANCE OF LANDING PARAMETERS BY VARYING THE RANGE VALUES

The following case study was done to determine the variation in the landing performance of the aircraft while varying the range at which the descent starts for the given aircraft. The Case study was done for different parameters like Angle of Attack, Elevator Command, Height, Pitch rate, Pitch and Sink rate. These parameters are varied for different value of ranges and their responses are compared. The different range values considered for this case study are 23,000 ft, 20000 ft, 15000 ft and 10,000 ft.

6.6.1 Variation of Angle of Attack

![Figure 6.43 Response of Angle of Attack Variations](image)

From Figure 6.43 an insight into the variation of the angle of attack with the variation of the range from which the descent starts is shown. The significant feature in analyzing the angle of attack is to check whether it lies within the limits specified in Table 5.1 when the range is varied for different values. From Table 6.4 it is observed that the angle of attack is steep for the
ranges of values between 10,000 ft-15,000 ft. when compared to larger values of the range(20,000-23,000) which is shown in Table 6.5.

6.6.2 Variation of Elevator Command

Figure 6.44 shows the variation of the elevator deflection, with the variation of the range at which the descent starts. If the landing starts at a larger value of the range, it is seen from the response curve the value of the elevator command is less which is recommended for good landing by MIL-STD 8785B. On the other hand, when the range is small, the elevator deflection occurs over a short period of time. This leads to landing mishaps due to actuator failure. Tables 6.4 and 6.5 ensure the above stated facts.

![Figure 6.44 Response of Elevator Deflection Variation](image)

6.6.3 Variation of Forward Velocity

From Figure 6.45 it is seen that when the descent starts from a point which is closer to the touch down point, the variation of the velocity of the
aircraft occurs at a very short period of time when compared to the descent that starts from the other successive points. Hence in this case, the change of the same velocity over a shorter period of time causes a greater force to act on the vehicle, thereby causing discomfort to the crew and passengers.

![Graph showing response of forward velocity variation](image)

**Figure 6.45 Response of Forward Velocity Variation**

### 6.6.4 Variation of Height

From Figure 6.46 it is viewed that there is a change in the variation of the height of the aircraft with a change in the range at which the descent starts. For the case when the descent starts from a short range, the variation of the height is also similar to that of the range, as both height and range are interdependent, so that a constant flight path angle is maintained. Therefore, the vertical descent rate will be steep for a smaller range value.
6.6.5 Variation of Pitch Rate

From Figure 6.47 it is seen that the pitch rate variation is similar in all the cases for most of the flight path, barring the few initial moments of the descent. The reason is that, when the descent starts from a short range and a large amount of variation has to be made in the elevator command. Thus the necessary height is attained in order to maintain the constant flight path angle.
6.6.6 Variation of Pitch

From Figure 6.48 it is seen that when the descent begins from a shorter range the change in the value of pitch angle is more. Hence, to attain the required value of the flight path angle, the aircraft’s pitch angle changes more abruptly.

![Figure 6.48 Response of Pitch Variation](image)

6.6.7 Variation of Sink Rate

From Figure 6.49 as mentioned earlier when the range at which the descent starts is small the descent rate becomes high in order to maintain the constant value of the flight path angle. Hence it is seen from the Figure that the value and the amount of variations in the sink rate are high and causes damage in the landing gear.
6.6.8 Variation of Throttle

From Figure 6.50 it is seen that in order to maintain the airspeed loop, the percentage value of the throttle increases for lower range values. It decreases for higher values of the range.
**Table 6.4  Typical Values of Parameters for Lower Value of Ranges**

<table>
<thead>
<tr>
<th>RANGE</th>
<th>Angle of Attack(deg)</th>
<th>Elevator Command</th>
<th>Forward Velocity(ft/s)</th>
<th>Height(ft)</th>
<th>Pitch(deg)</th>
<th>Pitch rate(deg/sec)</th>
<th>Throttle</th>
<th>Elevator Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0-10)</td>
<td>(10-30)</td>
<td>(30-50)</td>
<td>(50-80)</td>
<td>(0-10)</td>
<td>(10-30)</td>
<td>(30-50)</td>
<td>(50-80)</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>8.7 : -0.8</td>
<td>7.5 : 6.2</td>
<td>6.25 : 6.1</td>
<td>6 : -4.1</td>
<td>8.22 : -0.6</td>
<td>7.7 : 6.0</td>
<td>6.4 : 5.9</td>
<td>6.15 : -0.5</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>7.3 : 15.2</td>
<td>-2.9 : -6.2</td>
<td>-3.9 : -4</td>
<td>0.0 : -4.0</td>
<td>8.4 : -13</td>
<td>-2.7 : -5.9</td>
<td>-4.1 : -5.7</td>
<td>0.0 : -4.0</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>5.25 : -3.2</td>
<td>5.5 : 4.35</td>
<td>5.65 : 5.3</td>
<td>5.7 : -0.8</td>
<td>4.9 : -2.7</td>
<td>5 : 3.75</td>
<td>5.6 : 3.65</td>
<td>5.75 : -0.8</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>8.1 : -7.2</td>
<td>1 : -0.5</td>
<td>0.0 : 0.0</td>
<td>6.8 : -14</td>
<td>5.8 : -7</td>
<td>0.05 : -0.05</td>
<td>0.3 : -0.3</td>
<td>6.8 : -14</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>0.3 : 0.0</td>
<td>0.3 : 0.195</td>
<td>0.22 : 0.215</td>
<td>0.22 : 0.0</td>
<td>0.29 : 0.0</td>
<td>0.29 : 0.19</td>
<td>0.22 : 0.185</td>
<td>0.23 : 0.0</td>
</tr>
<tr>
<td>MAX:MIN</td>
<td>665 : -130</td>
<td>0.0 : 0.0</td>
<td>0.0 : 0.0</td>
<td>0.0 : 0.0</td>
<td>200 : -4450</td>
<td>0.0 : 0.0</td>
<td>0.0 : 0.0</td>
<td>0.0 : 0.0</td>
</tr>
</tbody>
</table>
Table 6.5  Typical Values of Parameters for Higher Value of Ranges

<table>
<thead>
<tr>
<th>RANGE</th>
<th>PARAMETERS</th>
<th>At 20,000 ft</th>
<th>At 23,000 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time in (sec)</td>
<td>Time in (sec)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0-10)</td>
<td>(10-30)</td>
<td>(30-50)</td>
</tr>
<tr>
<td>Elevator Command</td>
<td>8.2 : -0.42</td>
<td>7.8 : 6.2</td>
<td>6.15 : 5.7</td>
</tr>
<tr>
<td>Pitch (deg)</td>
<td>4.6 : 2.42</td>
<td>4.8 : 4.25</td>
<td>4.25 : 3.15</td>
</tr>
<tr>
<td>Pitch rate (deg/sec)</td>
<td>4.8 : -6.5</td>
<td>0.14 : -0.055</td>
<td>0.2 : -0.3</td>
</tr>
<tr>
<td>Throttle</td>
<td>0.28 : 0.0</td>
<td>0.28 : 0.195</td>
<td>0.195 : 0.19</td>
</tr>
<tr>
<td>Elevator Deflection</td>
<td>150 : -50</td>
<td>0.0 : 0.0</td>
<td>0.0 : 0.0</td>
</tr>
</tbody>
</table>
6.7 CONCLUSION

The transition from glide slope tracking to the flare maneuver was initially performed using a threshold switch based on the altitude. This switching process led to the requirement of large control effort, driving the actuators into saturation. This causes more oscillations in pitch angle and elevator deflection. During transition from glide slope to flare path the UAV will have a sudden change warranting more deflection in the elevator command which is not recommended during UAV landing process. An attempt has been made to overcome this transition problem, for which the author has formulated a new concept called as “Blending function”. This blending function provides a weighted combination of glide slope and flare controller commands during the transition between glide slope to flare. From the simulation results, it was inferred that the blending of signals during transition from glide slope to flare solves the problem of instability and extreme oscillations. Successful landings were tried and demonstrated at simulated airports around the world showing the versatility of the landing controller.

The case study, gives an insight into the variation of the various aircraft parameters when the range for the landing is varied. The flight path angle was maintained constant and the height and sink rate and other related parameters vary accordingly. This shows that the algorithm holds good for all the different range values selected. With all the responses obtained it is lucidly viewed that the performances of various parameters are not ideal for smaller values of the range. Therefore, it is concluded that the UAV can land without much disturbance if the value of range is chosen from 20,000ft to 23,000ft.