TABLE 13.5
Control actions.

	y												
x	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
−6	7	6	7	6	7	7	7	4	4	2	0	0	0
−5	6	6	6	6	6	6	6	4	4	2	0	0	0
−4	7	6	7	6	7	7	7	4	4	2	0	0	0
−3	6	6	6	6	6	6	6	3	2	0	−1	−1	−1
−2	4	4	4	5	4	4	4	1	0	0	−1	−1	−1
−1	4	4	4	5	4	4	1	0	0	0	−3	−2	−1
0+	4	4	4	5	1	1	0	−1	−1	−1	−4	−4	−4
0+	4	4	4	5	1	1	0	−1	−1	−1	−4	−4	−4
1	2	2	2	2	0	0	−1	−4	−4	−3	−4	−4	−4
2	1	1	1	−2	0	−3	−4	−4	−4	−3	−4	−4	−4
3	0	0	0	0	−3	−3	−6	−6	−6	−6	−6	−6	−6
4	0	0	0	−2	−4	−4	−7	−7	−7	−6	−7	−6	−7
5	0	0	0	−2	−4	−4	−6	−6	−6	−6	−6	−6	−6
6	0	0	0	−2	−4	−4	−7	−7	−7	−6	−7	−6	−7

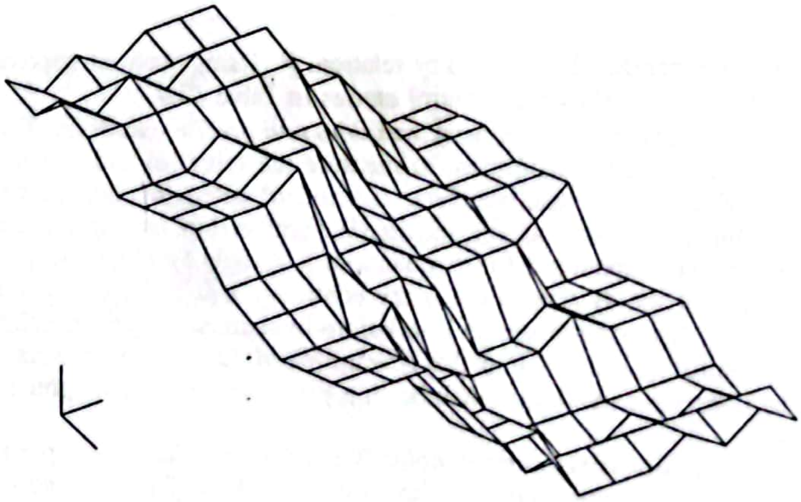

FIGURE 13.4
Control surface for fuzzy process control in Example 13.1.

Aircraft Landing Control Problem

The following example shows the flexibility and reasonable accuracy of a typical application in fuzzy control.

Example 13.2. We will conduct a simulation of the final descent and landing approach of an aircraft. The desired profile is shown in Figure 13.6. The desired downward velocity is proportional to the square of the height. Thus, at higher altitudes, a large downward velocity is desired. As the height (altitude) diminishes, the desired downward velocity gets smaller and smaller. In the limit, as the height becomes vanishingly small, the downward velocity

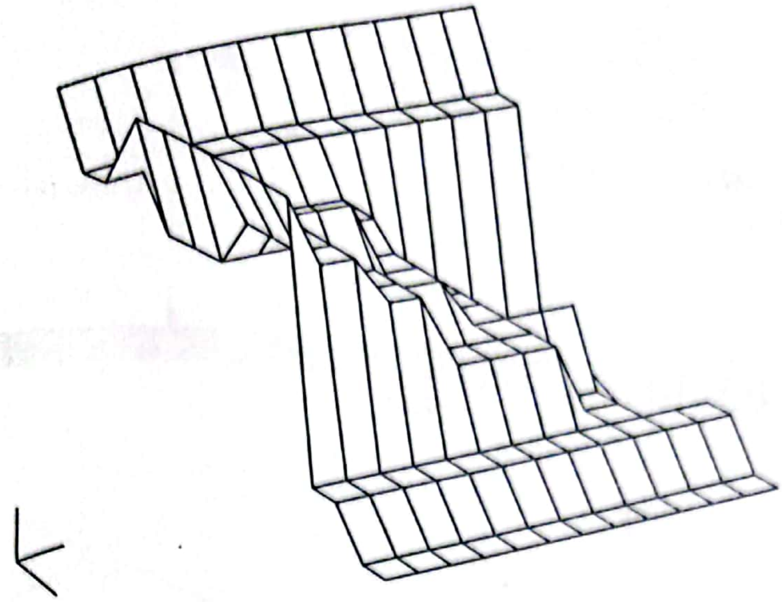

FIGURE 13.5
Control surface for crisp process control in Example 13.1.

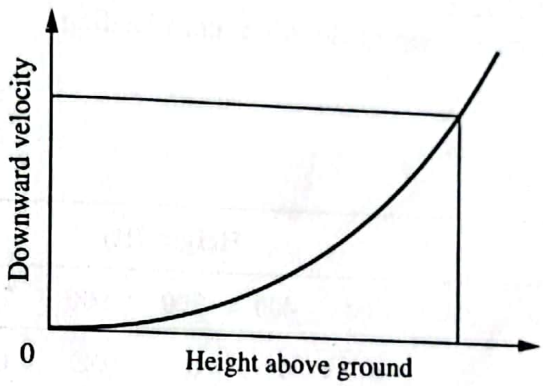

FIGURE 13.6
The desired profile of downward velocity versus altitude.

also goes to zero. In this way, the aircraft will descend from altitude promptly but will touch down very gently to avoid damage.

The two state variables for this simulation will be the height above ground, h, and the vertical velocity of the aircraft, v (Figure 13.7). The control output will be a force that, when applied to the aircraft, will alter its height, h, and velocity, v. The differential control equations are loosely derived as follows. See Figure 13.8. Mass m moving with velocity v has momentum $p = mv$. If no external forces are applied, the mass will continue in the same direction at the same velocity, v. If a force f is applied over a time interval Δt, a change in velocity of $\Delta v = f\Delta t/m$ will result. If we let $\Delta t = 1.0$ (s) and $m = 1.0$ (lb s^2 ft^{-1}), we obtain $\Delta v = f$(lb), or the change in velocity is proportional to the applied force.

In difference notation, we get

$$v_{i+1} = v_i + f_i,$$
$$h_{i+1} = h_i + v_i \cdot \Delta t,$$

where v_{i+1} is the new velocity, v_i is the old velocity, h_{i+1} is the new height, and h_i is the old height. These two "control equations" define the new value of the state variables v and

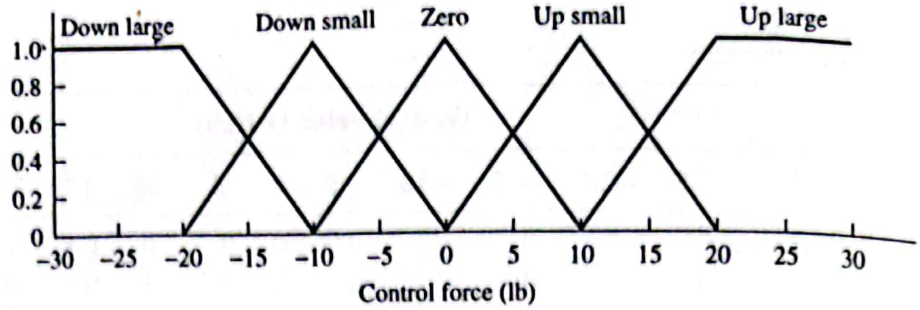

FIGURE 13.11
Control force, f, partitioned.

TABLE 13.9
FAM table.

	Velocity				
Height	**DL**	**DS**	**Zero**	**US**	**UL**
L	Z	DS	DL	DL	DL
M	US	Z	DS	DL	DL
S	UL	US	Z	DS	DL
NZ	UL	UL	Z	DS	DS

if height large
velocity down large
then force is zero

Initial height, h_0 : 1000 ft

Initial velocity, v_0 : -20 ft s^{-1}

Control f_0 : to be computed

Height h fires L at 1.0 and M at 0.6

Velocity v fires only DL at 1.0

if h near zero & velocity zero then force zero

fuzzy set height

Height		Velocity		Output
L (1.0)	AND	DL (1.0)	$\Rightarrow$	Z (1.0)
M (0.6)	AND	DL (1.0)	$\Rightarrow$	US (0.6)

We defuzzify using the centroid method and get $f_0 = 5.8$ lb. This is the output force computed from the initial conditions. The results for cycle 1 appear in Figure 13.12. Now, we compute new values of the state variables and the output for the next cycle:

$$h_1 = h_0 + v_0 = 1000 + (-20) = 980 \text{ ft},$$

$$v_1 = v_0 + f_0 = -20 + 5.8 = -14.2 \text{ ft s}^{-1}.$$

Height $h_1 = 980$ ft fires L at 0.96 and M at 0.64

Velocity $v_1 = -14.2$ ft s^{-1} fires DS at 0.58 and DL at 0.42

Height		Velocity		Output
L (0.96)	AND	DS (0.58)	$\Rightarrow$	DS (0.58)
L (0.96)	AND	DL (0.42)	$\Rightarrow$	Z (0.42)
M (0.64)	AND	DS (0.58)	$\Rightarrow$	Z (0.58)
M (0.64)	AND	DL (0.42)	$\Rightarrow$	US (0.42)

We find the centroid to be $f_1 = -0.5$ lb. Results are shown in Figure 13.13.

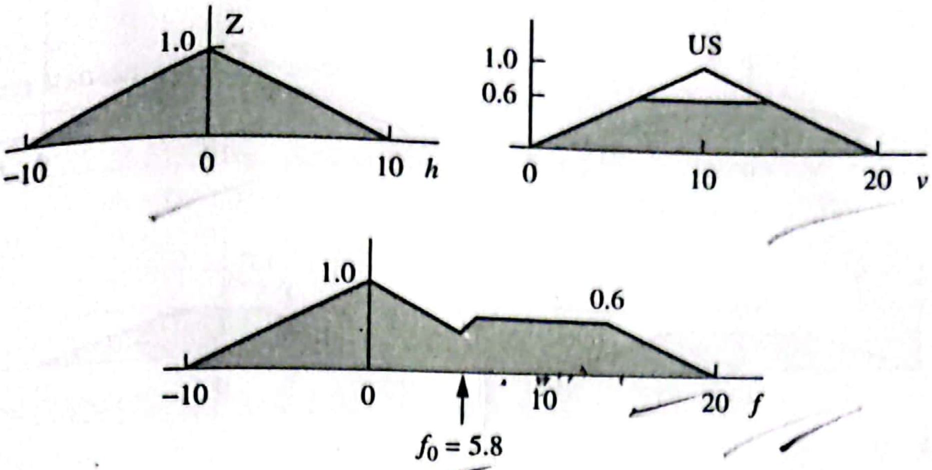

FIGURE 13.12
Truncated consequents and union of fuzzy consequent for cycle 1.

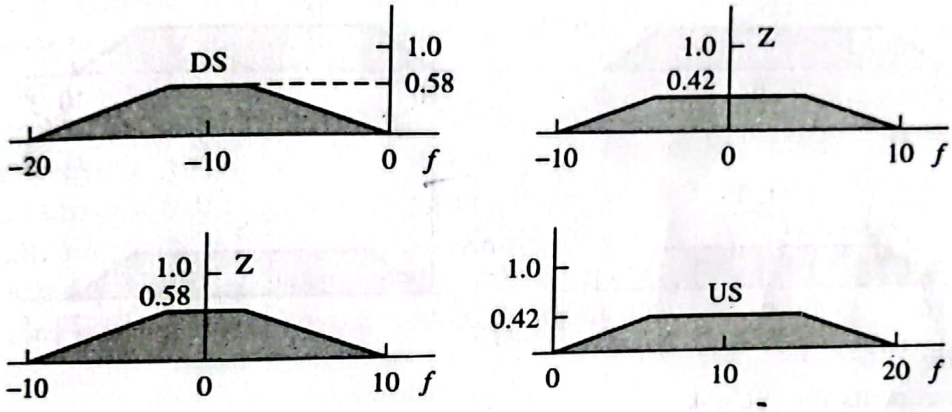

FIGURE 13.13
Truncated consequents for cycle 2.

We compute new values of the state variables and the output for the next cycle.

$$h_2 = h_1 + v_1 = 980 + (-14.2) = 965.8 \text{ ft},$$
$$v_2 = v_1 + f_1 = -14.2 + (-0.5) = -14.7 \text{ ft s}^{-1}.$$
$$h_2 = 965.8 \text{ ft fires L at } 0.93 \text{ and M at } 0.67,$$
$$v_2 = -14.7 \text{ ft s}^{-1} \text{ fires DL at } 0.43 \text{ and DS at } 0.57.$$

Height		Velocity		Output
L (0.93)	AND	DL (0.43)	⇒	Z (0.43)
L (0.93)	AND	DS (0.57)	⇒	DS (0.57)
M (0.67)	AND	DL (0.43)	⇒	US (0.43)
M (0.67)	AND	DS (0.57)	⇒	Z (0.57)

We find the centroid for this cycle to be $f_2 = -0.4$ lb. Results appear in Figure 13.14. Again, we compute new values of state variables and output:

$$h_3 = h_2 + v_2 = 965.8 + (-14.7) = 951.1 \text{ ft},$$
$$v_3 = v_2 + f_2 = -14.7 + (-0.4) = -15.1 \text{ ft s}^{-1},$$

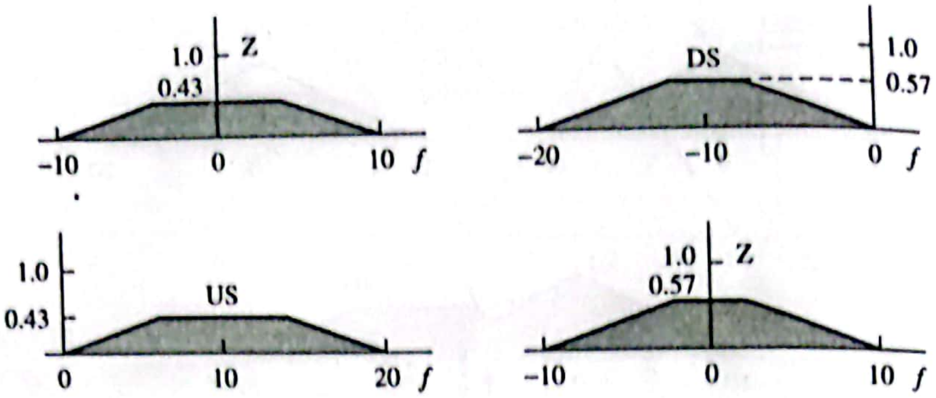

FIGURE 13.14
Truncated consequents for cycle 3.

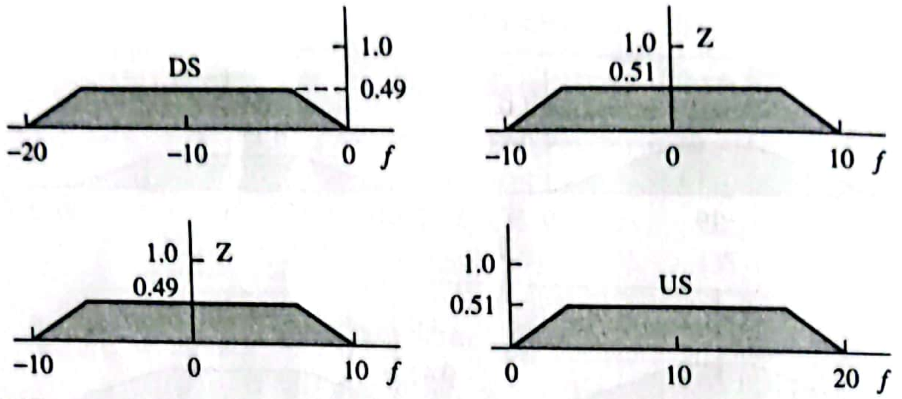

FIGURE 13.15
Truncated consequents for cycle 4.

and for one more cycle we get   cycle 4

$$h_3 = 951.1 \text{ ft fires L at 0.9 and M at 0.7},$$

$$v_3 = -15.1 \text{ ft s}^{-1} \text{ fires DS at 0.49 and DL at 0.51}.$$

Height		Velocity		Output
L (0.9)	AND	DS (0.49)	$\Rightarrow$	DS (0.49)
L (0.9)	AND	DL (0.51)	$\Rightarrow$	Z (0.51)
M (0.7)	AND	DS (0.49)	$\Rightarrow$	Z (0.49)
M (0.7)	AND	DL (0.51)	$\Rightarrow$	US (0.51)

The results are shown in Figure 13.15, with a defuzzified centroid value of $f_3 = 0.3$ lb. Now, we compute the final values for the state variables to finish the simulation:

$$h_4 = h_3 + v_3 = 951.1 + (-15.1) = 936.0 \text{ ft},$$

$$v_4 = v_3 + f_3 = -15.1 + 0.3 = -14.8 \text{ ft s}^{-1}.$$

The summary of the four-cycle simulation results is presented in Table 13.10. If we look at the downward velocity versus altitude (height) in Table 13.10, we get a descent profile that appears to be a reasonable start at the desired parabolic curve shown in Figure 13.6 at the beginning of the example.

TABLE 13.10
Summary of four-cycle simulation results.

	Cycle 0	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Height (ft)	1000.0	980.0	965.8	951.1	936.0
Velocity (ft s^{-1})	−20	−14.2	−14.7	−15.1	−14.8
Control force	5.8	−0.5	−0.4	0.3	

FUZZY ENGINEERING PROCESS CONTROL

Engineering process control, or the automatic control of physical processes, is a rather large complex field. We discuss first some simple concepts from classical process control in order to provide a background for fuzzy process control concepts. Since fuzzy process control systems can be very complex and diverse, we present only enough information here to provide an introduction to this very interesting topic. We first discuss the classical PID controller (Equation (13.7)), then some fuzzy logic controllers. Of the two types of control problems, setpoint tracking and disturbance rejection, we will illustrate only the setpoint-tracking problem. Most industrial problems are SISO, or at least treated that way because multi-input, multi-output (MIMO) problems are normally significantly more difficult. Fuzzy MIMO problems will be discussed in this chapter because fuzzy controllers usually handle these problems quite well; of the many types, only feedback control systems will be illustrated (Parkinson, 2001).

Classical Feedback Control

The classical feedback control system can be described using a block flow diagram like the one shown in Figure 13.16.

The first rectangular block in the figure represents the controller. The second rectangular block represents the system to be controlled, often called the *plant*. The block in the feedback loop is a converter. The *converter* converts the feedback signal to a signal

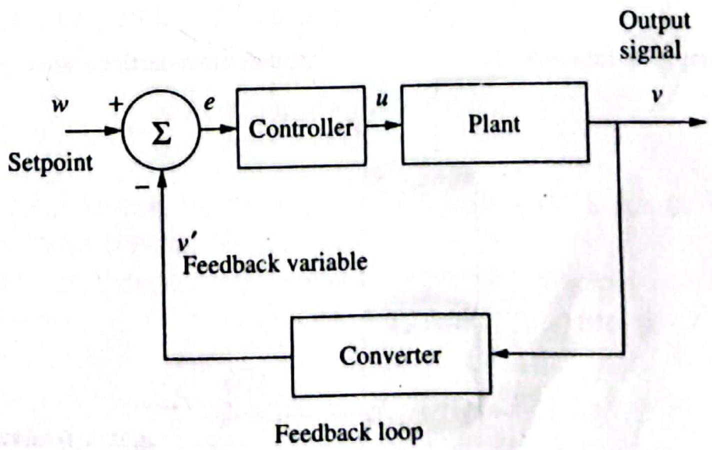

FIGURE 13.16
andard block flow diagram for a control system.