DYNACOMP

FLIGHT
SIMULATOR

NORTH STAR

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MICROCOMPUTER FLIGHT SIMULATOR
VERSION 2.0

The following discussion describes the basic operation of the MICROCOMPUTER FLIGHT SIMULATOR which appeared in the book SIMULATION, Programming Techniques Volume 2, published by BYTE Publications, copyright 1979. In the section entitled "Simulation of Flight", the program is treated in great detail, including flow charts, derivation of the simulation equations, as well as considerable explanation of the characteristics by way of example. This document is meant to supply only the information required to actually exercise the simulation using console commands.

The first user response reqired is whether or not instructions are desired. As in most cases, the prompts are self-explanatory. Thus we will concentrate only on those inputs which may be a little confusing. The first set of inputs which require some explanation are the "flight characteristics" section. Here the user defines the basic operational properties of the aircraft via a set of parameters. The first is the plane mass in tons (English units). The second is the fuel load, also in tons. The third is the thrust fraction, which means the thrust (push/pull) as a fraction of the plane's mass. Thus a one ton plane having a thrust of .3 would have 600 pounds push/pull (eg., the propeller would exert a force of 600 pounds on the plane). The fourth parameter is the maximum plane speed in knots. This refers to the level (neither ascending or descending) flight speed under full throttle. The fifth parameter is the glide angle. This is the minimum angle of glide if the engine is off (thrust=0) and the flight speed is near stall. The angle is in degrees. The sixth input is the time increment in seconds. The relevance of the number is simple. If the take-off option is chosen, then this is the time step between commands. However, once in the air, as will be discussed shortly, the time increment can be changed whenever you are in the command mode.

A suggested set of flight characteristics parameters is:

Plane mass- one ton
Fuel mass- 0.3 tons
Thrust fraction- .3
Maximum speed- 180 knots
Glide angle- 11 degrees
Time increment- 3 seconds

One of two flight modes may be initially chosen; take-off and in-the-air flight. In the take-off mode, there are three requested inputs every command time increment. They are thrust, flaps and elevator angle. The thrust input must be between -1 and +1. This is the fraction of maximum power which is to be applied. A 1 means full power; a 0, no power. Note that the thrust can be reversed for braking. The flaps input refers to the desired flap angle, which must be between 0 and 45 degrees. Full flaps is 45 degrees. A high flap angle increases lift, reduces the stall speed and increases the drag. The third input, elevator angle, effectively changes the angle of attack and affects the lift and attitude. For example, if during level flight the elevator angle is increased, the nose of the plane will rise relative to the horizon, and the plane will begin to climb. The normal range of elevator control is -20 to +20 degrees. Remember, the plus direction tends to pull the nose of the plane up.

The other command mode which requires explanation is the one which occurs once the plane is in the air. the initial prompt is "COCKPIT CONTROL?". A letter response is expected. The command letters are:

C: The program will continue with the previous set of command values.
S: A new time increment (in seconds) will be set by the next input.
T: A new throttle (or thrust) level will be set by the next input.
B: A new bank angle (in degrees) will be set according to the next input.
E: Similar to "B", but for the elevator angle.
F: Flaps; similar to E.
T: Trim angle. This can be set to a value between -10 and +10 degrees. It has the same effect as flaps and is controlled in the same manner. Ideally one would like to set the trim to a value such that level flight can be maintained with 0 flaps and 0 elevators (neutral controls). The plane would then be considered "in trim".
G: The next command input will set the landing gear to either an up or down position. 1 corresponds to down; 0 corresponds to up.

The in-flight command structure looks as follows:

```
        COCKPIT CONTROL LETTER:?<your command letter response><carriage return>
        CONTROL VALUE:?<control value><carriage return>
```

For example, to set the flaps to zero, and raise the landing gear, the command inputs would appear as follows:

```
        COCKPIT CONTROL LETTER:?F
        CONTROL VALUE:?0
        COCKPIT CONTROL LETTER:?G
        CONTROL VALUE:?0
        COCKPIT CONTROL LETTER:?C
```

Note that the "C" response ends the command session and the flight continues. This is a very important command.

There are many intricacies and complications involved flying. For further information on this simulation see the book cited above. Although the software supplied is an updated version, the line number references have been preserved. This update is mainly a compaction of the original listing shown in the book. A program, called "COMPRESS", which performs such compaction, is available from DYNACOMP. The two advantages associated with compacting programs written in BASIC are that the technique saves program memory space and the program executes faster.

& Another simulation, "VALDEZ", is also available from DYNACOMP. It deals with supertanker navigation in the Prince William Sound area of Alaska. A unique feature of this simulation is that the navigation is relative to a detailed 256X256 element map of that region. For further information, contact DYNACOMP, P.O. Box 162, Webster, New York, 14580.

```
RUN

MICROCOMPUTER FLIGHT SIMULATOR


VERSION NSF2.0
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```

Notes on running the MICROCOMPUTER FLIGHT SIMULATOR. The user is also referred to the book cited elsewhere for a take off sample listing.

```
THIS PROGRAM SIMULATES FLYING,
LANDING AND TAKE OFF.

DO YOU WISH INSTRUCTIONS? (Y/N): ?Y
```

- This option may not be available in highly compressed versions.

```
THERE ARE TWO POSSIBLE INITIAL
FLIGHT CONDITIONS; ONE WITH
PLANE 50 MILES FROM THE
AIRPORT AT AN ALTITUDE OF
SEVEN MILES, AND THE OTHER WITH
THE PLANE ON THE RUNWAY. THE
USER SUPPLIES THE FOLLOWING
CONSTANTS:
   *MASS OF THE PLANE
   *THRUST AS A FRACTION
    OF THE PLANE WEIGHT
   *MAX. LEVEL FLIGHT SPEED
   *GLIDE ANGLE AT STALL
   *ELEVATOR COEF. (NOSE)
   *TIME INCREMENT
CONTINUE?Y
```

- In the following, the "flight" option will be chosen. The alternative, "take off", is demonstrated in the book, SIMULATION, VOLUME 2.
- These are the parameters which determine the flight response of the plane. They are used within the program to calculate other constants, such as the drag coefficient.
- Note, the elevator response time coefficient has been removed from the latest versions.
- These prompts are designed for 16 line video displays in order to not miss output. Any key input (eg., carriage return) is sufficient.

```
THERE ARE TWO MESSAGE SETS.
ONE IS A COCKPIT DISPLAY WHICH
IS SELF-EXPLANATORY. THE OTHER
IS A CONTROL TOWER MESSAGE
GIVING RANGE, DESCENT RATE AND
POSITION RELATIVE TO THE RUNWAY.
THE FLIGHT CONTROL FUNCTIONS ARE:
   C=CONTINUE WITH SAME
   T=FRACTION OF MAX THRUST
   B=BANK ANGLE IN DEGREES
   E=ELEVATOR (DEGREES)
   F=FLAPS (0 TO 45 DEG.)
   R=TRIM (DEGREES)
   G=LANDING GEAR (0 UP/1 DN)
   S=NEW TIME INCREMENT
CONTINUE?Y
```

- Continue with the same values as given earlier.
- Maximum thrust fraction is 1 (or -1).
- Used to make turns.
- Used to go up and down.
- Used to increase lift for take off and landing.
- When adjusted properly, neutral controls will result in level flight.
- This sets the time step to the next control input. The plane flies for this length of time without pilot interaction.

```
IT IS SUGGESTED THAT THE TAKE-
OFF OPTION BE FIRST CHOSEN FOR
EXPERIENCE. A GOOD STARTING
TIME INCREMENT IS THREE
SECONDS. A PRACTICAL SET OF
PARAMETERS FOR A SMALL PLANE
MIGHT BE: WEIGHT, ONE TON;
FUEL, 0.3 TONS; THRUST, 0.3;
MAXIMUM SPEED, 180 KNOTS; GLIDE
ANGLE, 11 DEGREES.

GOOD LUCK
CONTINUE?Y
```

- These parameter values will result in a plane with good lift properties. However, it will be overly responsive. Note that it is very easy to specify a jet fighter or 747. Note, do not stray far from 11 degrees for the glide angle.

```
DO YOU WISH INSTRUCTIONS? (Y/N): ?H
 (Y/N): ?N
DO YOU WISH TO FLY (TYPE F)
OR TAKE-OFF (TYPE T):?F
```

- This is another example in which the instructions option was not chosen. Observe the input error check and re-try.
- The "flight" option is chosen.

```
INPUT THE FOLLOWING PARAMETERS:
MASS (TONS): ?1
FUEL (TONS): ?.3
THRUST FRACTION: ?.3
MAXIMUM SPEED (KNOTS): ?180
GLIDE ANGLE (DEGREES):?11
TIME INCREMENT (SECONDS):?3


READY FOR FLIGHT


*********************************
```

- This is the parameter input which is referred to elsewhere in the documentation.
- The thrust fraction terminolgy may cause some confusion. As used here, it represents the the maximum engine "pull". During the flight it refers to the portion of this power which is to be applied.

```
ALT.:  15832 FEET
SPEED:  135 KNOTS
STALL SPEED:  56 KNOTS
ENGINE TEMP:  280 DEG
FUEL 598 LBS.
FLAPS:  0 DEGREES
TRIM:  -10 DEGREES
THRUST:  .3
BANK:  0 DEGREES
ATTACK ANGLE:  0 DEGREES
HORIZON:  0 DEGREES
HEADING OFF EAST:  45 DEG.
LANDING GEAR:  UP
FLIGHT TIME:  .05 MIN.
CONTINUE?Y
```

- Below the stall speed, lift rapidly decreases. If the engine overheats, it will shut down.
- This parameter can be set by the pilot. Some experimentation will be required to arrive at a value which allows neutral flight.
- Perhaps the most important variable.
- Direction of the plane's flight path.

```
CONTROL TOWER MESSAGE
*********************************
RANGE:  50 MILES
CLIMB RATE:  0 FEET/SEC
POSITION OFF RUNWAY:  135 DEG.
WIND DIRECTION:  45 DEG.
WIND SPEED:  0 KNOTS
CONTINUE?Y
```

- Range is relative to the west end of the runway.
- Again relative to that end of the runway.
- Relative to east.
- Speed is rounded to nearest knot.

```
COCKPIT CONTROLS
*********************************

COCKPIT CONTROL LETTER:?T
CONTROL VALUE:?0


COCKPIT CONTROL LETTER:?E
CONTROL VALUE:?-4


COCKPIT CONTROL LETTER:?C
*********************************
```

- The general sequence is a control letter followed by a control value, except for the "C" (continue) control.
- An illegal control letter will be accepted, but no action will be taken. However, a control value will also be required for bookkeeping.

```
ALT.:  15834 FEET
SPEED:  124 KNOTS
STALL SPEED:  62 KNOTS
ENGINE TEMP:  170 DEG
FUEL 598 LBS.
FLAPS:  0 DEGREES
TRIM:  -10 DEGREES
THRUST:  0
BANK:  0 DEGREES
ATTACK ANGLE:  -3 DEGREES
HORIZON:  -3.3 DEGREES
HEADING OFF EAST:  45 DEG.
LANDING GEAR:  UP
FLIGHT TIME:  .1 MIN.
CONTINUE?Y
```

- Note the changes in the flight conditions due to the 3 second time interval.
- The changes shown are extreme as the engine was shut down while traveling relatively fast. Rapid deceleration is apparent.

THERE ARE TWO POSSIBLE INITIAL FLIGHT CONDITIONS; ONE WITH PLANE 50 MILES FROM THE AIRPORT AT AN ALTITUDE OF SEVEN MILES, AND THE OTHER WITH THE PLANE ON THE RUNWAY. THE USER SUPPLIES THE FOLLOWING CONSTANTS:

- *MASS OF THE PLANE
- *THRUST AS A FRACTION OF THE PLANE WEIGHT
- *MAX. LEVEL FLIGHT SPEED
- *GLIDE ANGLE AT STALL
- *ELEVATOR COEF. (NOSE)
- *TIME INCREMENT

THERE ARE TWO MESSAGE SETS. ONE IS A COCKPIT DISPLAY WHICH IS SELF-EXPLANATORY. THE OTHER IS A CONTROL TOWER MESSAGE GIVING RANGE, DESCENT RATE AND POSITION RELATIVE TO THE RUNWAY. THE FLIGHT CONTROL FUNCTIONS ARE:

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T=FRACTION OF MAX THRUST
B=BANK ANGLE IN DEGREES
E=ELEVATOR (DEGREES)
F=FLAPS (0 TO 45 DEG.)
R=TRIM (DEGREES)
G=LANDING GEAR (0 UP/1 DN)
S=NEW TIME INCREMENT

IT IS SUGGESTED THAT THE TAKE-OFF OPTION BE FIRST CHOSEN FOR EXPERIENCE. A GOOD STARTING TIME INCREMENT IS THREE SECONDS. A PRACTICAL SET OF PARAMETERS FOR A SMALL PLANE MIGHT BE: WEIGHT, ONE TON; FUEL, 0.3 TONS; THRUST, 0.3; MAXIMUM SPEED, 180 KNOTS; GLIDE ANGLE, 11 DEGREES.

GOOD LUCK

Notes which are included in the unabridged versions of the MICROCOMPUTER FLIGHT SIMULATOR.

Simulation of Flight

F.R. Ruckdeschel

Several years ago, at a trade show in the New York City Coliseum, I saw a demonstration that simulated the flight of an airplane between two pylons. The simulation employed a cartoon-like representation of the pilot's cockpit view on a large video screen. The pilot interaction was via a joystick. When given a chance to test my own skill, I crashed.

The demonstration was impressive, particularly because it was in real time and attempted to mimic the flight of an actual flying machine. The major time cruncher in that animation was probably the display update. Today's microcomputer is capable of analogous *system simulations*.

The simulation presented here treats the flight characteristics of the model airplane using aerodynamic equations. For display purposes the model assumes zero visibility flight conditions in which the cockpit window view is replaced with an instrument panel readout and control tower communications. This type of interaction is much more technical than the simple graphics display, and perhaps more realistic.

To further enhance the realism, many standard cockpit controls have been simulated, including elevators, rudder, ailerons, flaps and throttle. These controls were individually defined and then combined into an overall flight model. The flight characteristics simulated involve several inertial and aerodynamic effects, including momentum, centrifugal force, air pressure, lift, drag and stall. The user chooses the basic flight characteristics which are used to represent an airplane design, ranging anywhere from a glider or Piper Cub to a jumbo jet or Phantom.

One objective of the flight simulation is to bring the plane down from a cruise altitude, 50 miles from an airport, to land on a two mile long runway (which can be shortened, if desired). The simulation portrays the landing itself, including deceleration once on the runway. Another objective is to take off from the same runway.

The extensive list of model features may best be understood by actually running the simulation or by reading through the mathematical and aerodynamical descriptions. Most users will initially have trouble flying the plane, and it may take some time to learn how to land it (probably after many crashes). The difficulty was created intentionally; flying a real airplane is not simple.

The simulation is considered in the context of a *system* model that contains various *subsystems* and *environments*, and whose output is the flight trajectory. The subsystems are the flight controls and displays. The three environments considered are takeoff, landing and flying. These three environments are linked through the executive. Transition from one to another is controlled automatically.

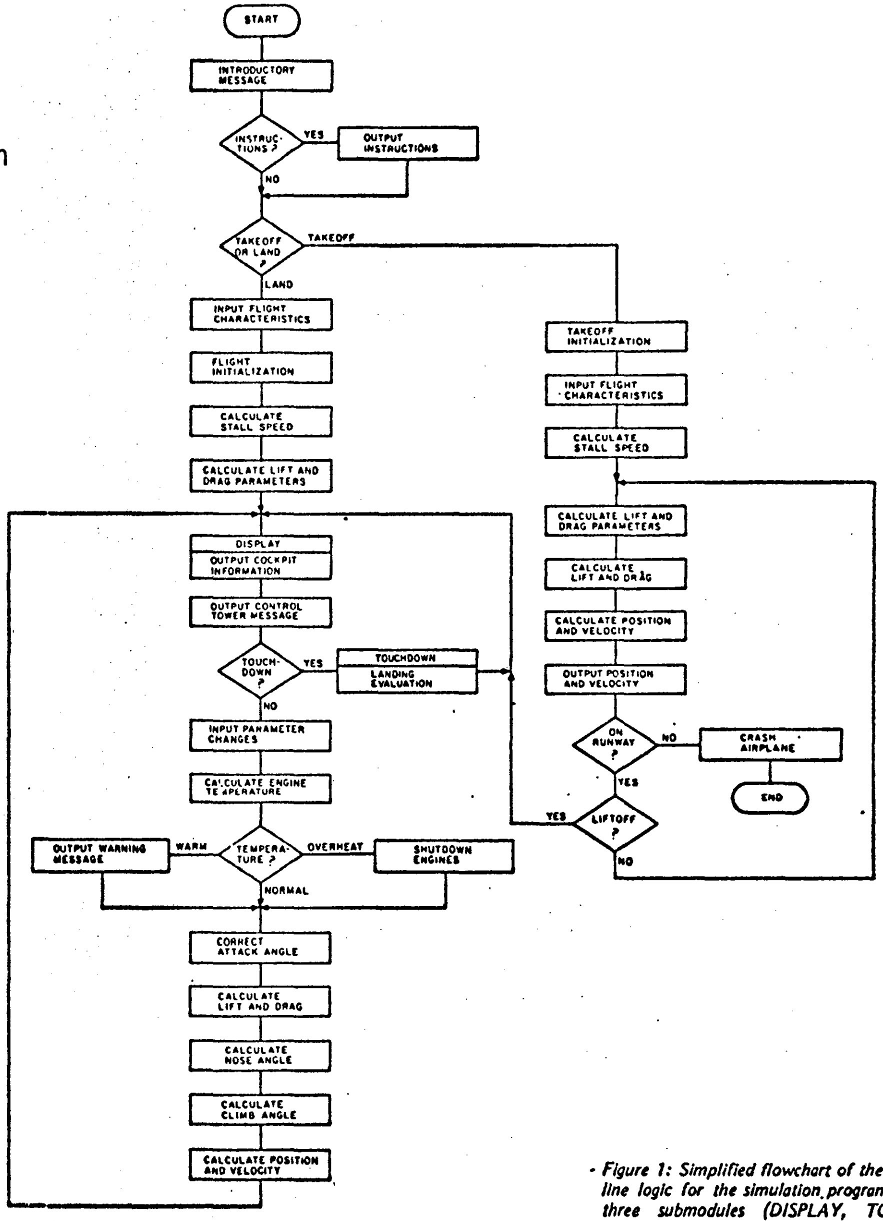

Figure 1: Simplified flowchart of the main-line logic for the simulation program. The three submodules (DISPLAY, TOUCHDOWN, and RUNWAY) are shown in figures 2 through 4.

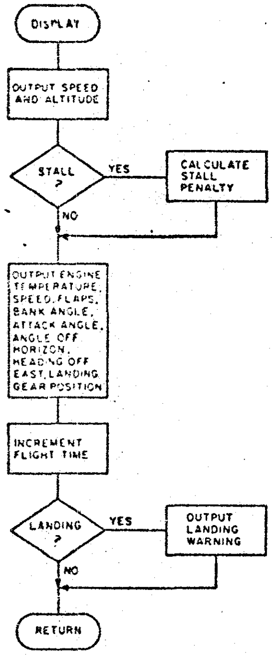

Figure 2: The DISPLAY routine outputs the cockpit controls for the pilot's reference.

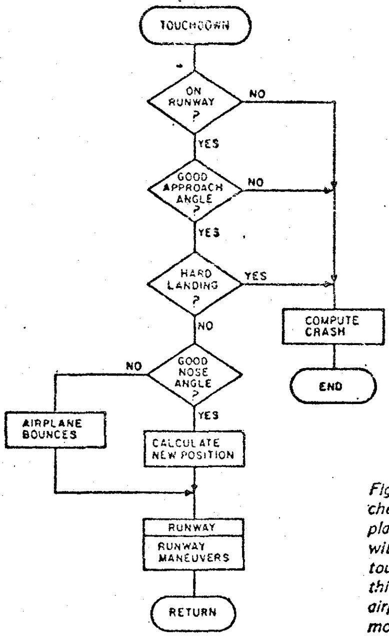

Figure 3: TOUCHDOWN checks to see if the airplane is correctly oriented with the runway when it touches down. If everything is not correct, the airplane will bounce or, more probably, crash.

A basic (and simplified) program flowchart of the executive structure is shown in figure 1. It consists of a group of checks, decisions and subroutine calls. Although the seven dimensional simulation appears complicated, it is broken down into manageable pieces. Also buried in the computations is a simple finite differences integration of some complicated nonlinear differential equations. The form of the calculations was laid out such that there is little chance of instability in the mathematical solution.

The reader is referred to the discussion in subsequent sections for explanations of the basic subroutines. Before proceeding, however, note that the cockpit display routine (see figure 2) is entered after the following conditions are obtained:

- flight has just started
- takeoff routine has resulted in liftoff
- runway maneuvers (after touchdown, figures 3 and 4) resulted in liftoff
- flight still in progress.

It should be apparent that the system oriented formatting of this model has many of the same elements in it as a general industrial machine simulation. The way this particular simulation was created was from the subsystems *up*. The flight equations were collected, as well as the various control models, into subroutines as it was already known that these were needed. It was then a simple matter to write a short executive which called them in the right order. Many simulation problems can be handled in this divide-and-conquer manner, given some idea of the final goal.

The actual physical models and equations used are very approximate. This brings us to a very interesting problem, since it might be said that the final simulation can be no better than its parts. However, the applicability of any particular system level model must be measured relative to the planned use. If the goal were to build an airplane based on the crude analyses used here, good luck! However, if the goal is to roughly simulate actual flight for a person having little flying experience, the level of accuracy applied is probably sufficient. This simulation is structured so that it is relatively easy to improve upon the submodels through simple replacement. It would be interesting to hear from readers with flight or aerodynamic experience about possible improvements and how they might affect the airplane response as perceived by the pilot.

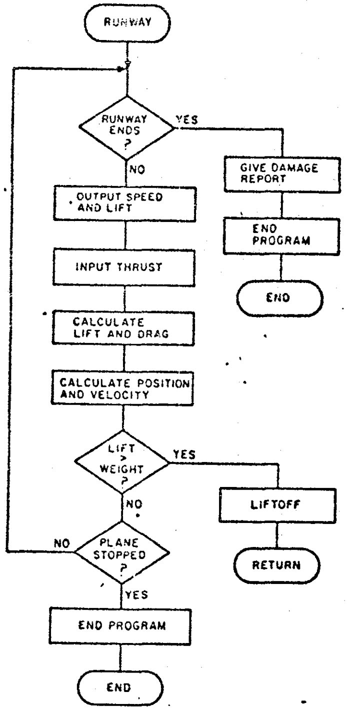

Figure 4: RUNWAY routine allows the pilot to maneuver the airplane on the ground. One of three conditions will cause an exit: run off end of runway, stop the airplane, lift off and start free flight.

Basic Governing Equations

Straight Line, Steady State Flight

There are several forces acting on a plane in flight. For this simulation we consider the forces of lift, drag, gravity and inertia. To make the flight behavior of the simulated airplane realistic, an approximation to the lift characteristics of an actual airfoil is used (NACA Airfoil #4412 as described in *Aerodynamics* by T von Karman, McGraw Hill (1963)):

$$L = C_L\,(0.4 + 5\theta_a)V^2 \quad (\theta_a < 0.28 = \theta_{amax}) \qquad (1)$$

C_L is the lift coefficient, θ_a the angle of attack in radians, and v the airfoil speed. A constraint is put on the maximum angle of attack, θ_{amax}, after which the lift coefficient abruptly falls (and presumably so does the plane). For airfoil # 4412 this attack angle limit is approximately 16° (0.28 radians).

The total drag is composed of a kinetic term induced by the air disturbance related to lift, C_{DI}, and a frictional term, C_{DF}:

$$D = C_{DI}(L^2/\rho v^2) + C_{DF}(\rho v) \qquad (2)$$

The normalized air density (ρ) is defined to be one at ground level.

The maximum thrust available will be described as a fraction (ζ) of the airplane weight, Mg, which is the mass of the plane (M) multiplied by the gravitational constant (g). At the maximum ground level flight speed of the airplane, v_{max}, the frictional drag is assumed to dominate, giving:

$$T_{max} = \zeta Mg = C_{DF}v_{max}.$$

The maximum thrust and maximum level flight ($\rho = 1$) velocity will be considered as chosen flight characteristics, so:

$$C_{DF} = (\zeta Mg)/v_{max}. \qquad (3)$$

Another chosen characteristic is the glide angle θ_g (no power) under maximum lift conditions (flaps fully down). This corresponds to the maximum angle of attack. Under these constraints $L = (Mg) \cdot \cos(\theta_g)$ and the stall speed (v_s) and coefficient of lift, C_L, may be related using equation (1):

$$C_L = \frac{(Mg)\cos(\theta_g)}{V_s^2\,(0.4 + 5\theta_{amax})} \qquad (4)$$

Under these particular low altitude, no power glide conditions, assume the frictional and induced drags to be equal when the landing gear is up (i.e.: from equation (2) $C_{DI}(L^2/\rho v^2) = C_{DF}(\rho v)$). The relation between the gravitational force and drag force along the glide path is:

$$(Mg)\sin(\theta_g) = 2\,C_{DF}v_s$$

or:

$$C_{DF} = \frac{(Mg)\sin(\theta_g)}{2v_s} \qquad (5)$$

This assumption regarding the equality of the two drags is equivalent to:

$$C_{DI} = C_{DF}(v_s)^3/(Mg\cos(\theta_g))^2 \qquad (6)$$

The variable which is key to evaluating C_L and C_{DI} is the stall speed v_s. Using equation (3) and the drag equality assumption (equation (5)) we get:

$$\xi(Mg)/v_{max} = (Mg)\sin(\theta_g/2v_s$$

or:

$$v_s = \frac{v_{max}\sin(\theta_g)}{2\xi} \qquad (7)$$

Equation (7) has a reasonable behavior. Assuming a plane with a thrust equal to one half of its weight (a fighter?) and a glide angle of roughly 11° (0.192 radians), then the stall speed is approximately two tenths of the maximum velocity. For a maximum velocity of 600 knots, the stall speed (flaps fully down) is calculated to be 120 knots.

To sum up, given the input parameters of plane mass, maximum thrust, and glide angle the key flight parameters required in equations (1) and (2) are obtained, as well as the stall speed.

To add to the realism of take off and final approach, the ability to manipulate flaps and landing gear is added. It is assumed that the effect of full flaps is to simply increase the airfoil lift coefficient by 50%. The effect of landing gear drag will be assumed to show up as a 60% increase in the frictional drag coefficient. Note that it is possible to create an underpowered plane that can't take off due to landing gear drag, but can fly with the gear raised. In approximation (equation (4), by inspection) we have for the relation of the stall speed with flaps to the non-flap stall speed:

$$v_s(f) = \sqrt{3/2}\, v_s(1)/(1+f/2)^{1/2} \qquad (8)$$

where $0 < f < 1$ represents the range from no flaps to full flaps. Of course, this is really only a guess since all of the flight parameters are not known.

In the simulation, penalties are placed on stalling the plane. Also, landing without the gear down will be considered a crash situation.

Changes in Flight

Changing horizon, heading, or speed can not be done instantaneously because of inertial effects. Also, pitch oscillations are possible in an overly responsive control system. The time lags associated with such controls are a vital part of the simulation.

A change in horizon or attack angle is accomplished with the elevators. The elevator angle (level of control) is represented by E. The rate of attack angle change ($d\alpha/dt$) is dependent on the control level and possibly plane speed. However, for this simulation assume

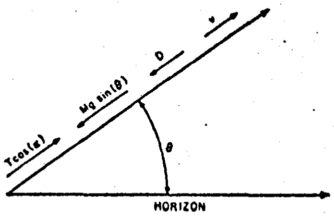

Figure 5: References used for calculating the motion along the flight path. The angle of flight is represented by θ.

$$\alpha = E \qquad (9)$$

The response to a change in throttle is specified in terms of an acceleration or deceleration. If the plane is in dynamic equilibrium, a change in throttle of ΔT leads to an instantaneous acceleration equal to the change in thrust divided by the mass of the airplane ($\Delta T/M$). Changes in lift cause a similar effect. This leads to the equation of motion along the flight path (see figure 5):

$$T\cos(\alpha) = Mg\sin(\theta) + D \qquad \text{(constant thrust)}$$

$$M\frac{dv}{dt} = T\cos(\alpha) - Mg\sin(\theta) - D \qquad \text{(changing thrust)}$$

or:

$$\frac{dv}{dt} = \frac{T\cos(\alpha)}{M} - g\sin(\theta) - D/M \qquad (10)$$

In a time interval Δt

$$\Delta v = \frac{T\cos(\alpha)}{M}\Delta t - (g\sin(\theta) + D/M)\Delta t$$

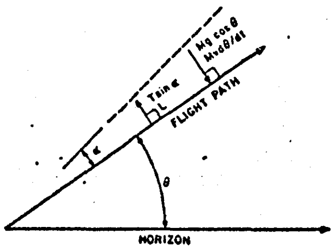

Figure 6: References used for calculating changes perpendicular to the flight trajectory. The angle of attack is represented by α.

The change in angle of climb depends on the force components perpendicular to the flight path (refer to figure 6). This includes thrust and lift.

The acceleration perpendicular to the flight path is related to the centrifugal force Mv^2/r, where r is the instantaneous loop radius. In terms of climb angle θ, the centrifugal force is $Mv \cdot d\theta/dt$. Balancing forces results in

$$L + T\sin(\alpha) - Mg\cos(\theta) = Mv\frac{d\theta}{dt}.$$

or:

$$\frac{d\theta}{dt} = \frac{T}{Mv}\sin(\alpha) - \frac{g\cos(\theta)}{v} + \frac{L}{Mv} \qquad (11)$$

Observe that a massive plane with a low power to mass ratio cannot change its climb angle rapidly. Also, the rate of angle change is shown to decrease with greater speed. These dependencies are intuitively reasonable.

Heading change is accomplished through a rudder and aileron control. In real life, the plane is put into a bank using the ailerons, which aid in supplying a tangential force to the trajectory. It is assumed that the pilot knows how to bank so that there is zero slip, as shown in figure 7. The addition of slip would be an interesting upgrade to the simulation, particularly in landing.

The centrifugal force is assumed to be balanced by the horizontal lift component, $L\sin(B)$, such that:

$$L\sin(B) = Mv^2/r$$

or:

$$\frac{d\rho}{dt} = \frac{L\sin(B)}{Mv} \qquad (12)$$

where ρ is the heading.

It is assumed the rudder and aileron controls instantaneously result in a correct value for the bank angle B. Note how the heading change is again shown to be slower for larger and faster planes (unless the lift is increased).

Equations (9), (10), (11) and (12) completely describe the kinematic changes in attack angle, speed, climb angle, and heading. The original equation (11) was written for nonbanked flight. When banking, the L term should be replaced by the term $L\cos(B)$ since turns have a detrimental effect on lift. We can now proceed to use this information and that of the last section to establish the finite difference equations that determine the airplane's trajectory.

Finite Difference Equations

At any point in time, the position of the airplane may be described by the vector: $\vec{x} = x\hat{i} + y\hat{j} + z\hat{k}$. The z variable is the altitude of the airplane. The airport runway is specified to start at $\vec{x} = 0$ and run to $\vec{x} = +c\hat{i}$. Airport radar headings and positions are stated relative to the beginning of the runway.

The finite difference equation giving the position at time $t + \Delta t$ is:

$$\vec{x}(t + \Delta t) = \vec{x}(t) + \vec{v}\Delta t. \qquad (13)$$

Similarly:

$$\vec{v}(t + \Delta t) = \vec{v}(t) + \frac{d\vec{v}}{dt}\Delta t. \qquad (14)$$

The task is largely one of finding $d\vec{v}/dt$ and thus $\vec{v}$. The rate of velocity change (acceleration) is composed of three basic components:

- Acceleration along the flight path
- Changes in the climb angle
- Turning.

The velocity changes are composed of two parts:

- Change along the trajectory
- Change in climb angle.

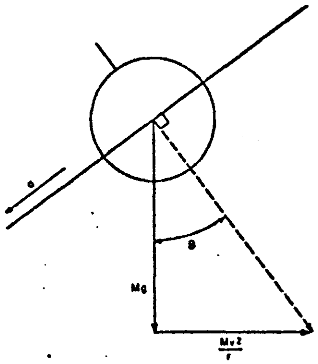

Figure 7: This simulation assumes that the airplane banks without slipping. (When banking without slip, the force vector a is zero.) The resultant force is perpendicular to the wings resulting in a change of direction.

The change along trajectory is given by:

$$\Delta\vec{v}_1 = \left(\frac{\vec{v}}{v}\right) \left\{\frac{T\cos(\alpha)}{M} - g\sin(\theta) - \frac{D}{M}\right\} \Delta t. \tag{15}$$

The change in the climb angle is a vector which is instantaneously perpendicular to the velocity vector. For simplicity we will assume the related velocity change to have only a vertical component scaled by the cosine of the climb angle:

$$\Delta\vec{v}_2 = v\cos(\theta)\frac{d\theta}{dt}\Delta t\hat{k} = v\cos(\theta)\left\{\frac{T}{Mv}\sin(\alpha) - \frac{g\cos(\theta)}{v} + \frac{L}{Mv}\right\}\Delta t\hat{k} \tag{16}$$

The third velocity change contribution is from the change in heading which is assumed to be only in the horizontal plane. Thus:

$$\Delta\vec{v}_3 = \left\{\frac{\hat{k} \times \vec{v}}{\sin(\theta)}\right\}\frac{dB}{dt}\Delta t = \frac{L\sin(B)}{v\cos(\theta)}\left\{v_x\hat{j} - v_y\hat{i}\right\}\Delta t \tag{17}$$

The notation $\hat{k} \times \vec{v}$ stands for the vector cross product. This is used as an approximation.

Combining the above equations we have:

$$\Delta v_x = \frac{\Delta t}{Mv}\left[\left\{T\cos(\alpha) - Mg\sin(\theta) - D\right\}v_x - \frac{L\sin(B)}{\cos(\theta)}v_y\right] \tag{18a}$$

$$\Delta v_y = \frac{\Delta t}{Mv}\left[\left\{T\cos(\alpha) - Mg\sin(\theta) - D\right\}v_y + \frac{L\sin(B)}{\cos(\theta)}v_x\right] \tag{18b}$$

$$\Delta v_z = \frac{\Delta t}{Mv}\left[\left\{T\cos(\alpha) - Mg\sin(\theta) - D\right\}v_z + v\cos(\theta)\left\{T\sin(\alpha) - Mg\cos(\theta) + L\right\}\right] \tag{18c}$$

Equation (18c) can be replaced by the more obvious equation:

$$v_z = v\sin(\theta).$$

Equations (18) are used in conjunction with equations (13) and (14) to give the updated velocity and position of the airplane. The constitutive equations are:

L: = lift (equation 1)
D: = drag (equation 2)
α: = attack angle (equation 9)
θ: = climb angle (equation 11)

Now that most of the theory of operation of the simulation has been covered, consider listing 1 which is the actual program being used.

The Program

Initial Conditions

The user designs an aircraft through the choice of a few simple initial flight values. The number of input parameters has been kept to a minimum by using approximate aerodynamic interrelations within the program. The parameter values suggested in the program text correspond to a small propeller driven plane carrying about four hours of fuel when at 80% throttle (thrust). Varying the following parameters will result in many interesting designs:

- Weight of Plane: Self-explanatory.
- Fuel: At the outset of the simulation the pilot inputs the fuel load in the same units as the mass of the airplane. The fuel usage during flight versus the throttle setting is assumed to be parabolic; full throttle eats up fuel rapidly. The constants were chosen such that under *normal* conditions, full throttle can be maintained for one to two hours before the fuel runs out. However, the engine will overheat long before that occurs.

One aerodynamic effect of fuel consumption is that the airplane weight changes with time. This is reflected in the airplane going out of trim.

- Thrust Fraction: This is the maximum *force* which can be exerted by the engine relative to the unladen airplane weight. Generally, a higher thrust fraction results in faster response to controls and the ability to climb rapidly. The engine power is derated exponentially with altitude, as is the lift. Thus, there is a built in ceiling (maximum level flight altitude) for all designs. If a space shuttle is to be simulated, the restriction on engine power P1 must be removed in line 1480 of listing 1.
- Maximum Speed and Glide Angle: These are key input design parameters which strongly determine the flight characteristics of the aircraft. The stall speed increases with increasing maximum speed. Stall speed is also an increasing function of glide angle. Planes with high maximum thrust ratios (maximum thrust versus plane weight) also tend to have relatively low stall speeds. These design parameters also affect the lift and drag coefficients in nonobvious ways. Experimentation is required to create an aircraft design which behaves well in the air. For example, choosing too low a glide angle can lead to a plane which tends to be overly responsive. An interesting classic design which might be tried is that corresponding to a Bell X1: high power; high maximum speed; poor speed and glide angle relation (must land at high speed to maintain lift). A two mile long runway might seem short in such a simulation.
- Time Increment: In the take off mode, the time increment value initially chosen sets the time steps for the entire take off sequence. The time increment can not be changed during a runway roll. Once in the air, the time increment can be changed as desired. Take off is not really very exciting or tricky (unless the craft is underpowered like the Spirit of St Louis), so a relatively long increment (about 5 seconds) may be used.

Internal Initializations

There are parameter initializations which occur within the program after the flight or take off option is chosen. When the flight option is chosen, the airplane's position is set to fifty miles from the airport with an associated altitude of seven miles. This can be changed by altering the values of X1, X2, and X3 on line 980 of listing 1. The initial speed is chosen to be three quarters maximum and the velocity vector is directed southeast. The velocity vector is described by the component values S1, S2, and S3; the speed (V) equals $\sqrt{S1^2+S2^2+S3^2}$. In this initialization case S3 (the vertical velocity component) is set equal to zero and S1 is equal to S2.

There are several other parameters which are automatically specified:

- Flaps are positioned up (F1=0)
- Angle of attack is zero (T1=0)
- Throttle is at 30% of maximum (T=.30 X maximum thrust)
- Bank angle set to zero (B=0)
- Engine temperature set to 280°F (T9 = 280)
- Trim angle is 0° (R9=0)
- Landing gear is up.

The net result of these initial conditions for the flight option is that the pilot takes over control of an airplane which is momentarily in level flight. The craft will most likely tend to climb or descend unless the control settings are changed. Thus, it is advisable to choose a small time increment when initially taking over the controls. Once the flight is stabilized, longer time increments may be used. The controls themselves are discussed later.

The take off option also leads to an initialization routine within the program. In this case all controls except trim are generally set to their zero positions. The trim is set to −10°. The airplane is parked at the beginning of the runway with the engine temperature set to 300°F.

Take Off Controls

There are only three controls exercised during take off: thrust, flaps, and elevators.

- Thrust: In the user initialization of the program, a value for the maximum thrust (jet push; propeller pull) in terms of a fraction of the airplane's weight is specified. This cannot be subsequently changed during a run. The engine control which does exist is that which determines how much of this potential thrust is applied over the next time period. This fraction is represented by T. Its maximum absolute value is unity, but it may be positive or negative. If positive, the plane accelerates; if negative, it decelerates and possibly rolls backwards. A reversible pitch propeller would permit this latter type of behavior.

For an average airplane, a reasonable take off value for the thrust is generally 0.8 to 1.0. Note, however, that maintaining a thrust value of 1.0 will eventually lead to overheating of the engine. A thrust of 0.8 can be sustained indefinitely.

- Flaps: The effect of flaps is to increase the lift of the plane at a given speed. In doing so, the drag is also increased. The flaps may be set to between 0° and 45°, with the maximum lift occurring at 45°. If an attempt is made to lower the flaps further, they will simply peg at the full flaps (45°) limit. Under normal take off conditions, half flaps (22.5°) is usually used from the beginning of the roll. For some aircraft design choices, the use of full flaps during the take off roll may result in so much drag that the required flight speed may not be reached by the end of the runway. The quickest take off sequence is achieved by employing zero flaps at the beginning of the roll and full flaps when the required air speed is attained. However, control of the plane as it leaves the ground then becomes tricky; the plane may sharply climb, decelerate, stall (drastically lose lift), and crash.
- Elevator Angle: The net effect of the elevator control is to raise or lower the nose of the airplane relative to its trajectory. When rolling on the ground, the elevator control causes the nose to point up or down relative to the horizon. The airplane's response to the controls is speed-dependent. If the airplane is stationary, the elevator control has no effect.

The maximum absolute value possible for the elevator control is 45°. This corresponds to the physical angle at which the elevators may be positioned, but is *not* the resultant nose angle; the control response is always less than the control setting unless the plane is in a high speed dive.

If the elevator angle is positive, the plane will tend to nose up. During the take off period the plane should be held down by setting the elevators slightly negative until a runway speed is attained which is roughly 20 knots greater than the stall speed. The elevator control may then be pulled forward (made a few degrees positive) to lift off.

Take Off Displays

The take off controls are exercised once each time period. The corresponding data displayed are the plane's horizon, runway speed, stall speed and lift, as well as the remaining runway length and flight time. A more detailed description of these displays follows.

- Horizon: When the plane is on the runway, the horizon angle is identical to the angle of attack as the trajectory is horizontal. In attempting to hold the plane down using the elevator control, the horizon will be negative. Upon lift off it will very likely be positive. The desirable range of horizon angles while on the runway is between perhaps −3° (during roll) and +5° (at lift off).
- Runway Speed: Self-explanatory.
- Stall Speed: The displayed stall speed will not change during the take off sequence, through it may during flight. Below the stall speed it is not possible to obtain sufficient lift to leave the ground. Do not attempt lift off just above the stall speed, since that leaves little room for error. For example, a small deceleration as the plane climbs off the runway can quickly lead to a stall. A 15% or greater margin in speed is advisable.
- Lift: This is a cockpit display which is not commonly found in small craft. It serves as a replacement for pilot *feel*. The lift readout is also available upon landing and is useful in determining whether or not another take off may be attempted. The value shown is simply the percent of the plane's weight which is aerodynamically supported. Take off occurs when this quantity exceeds 100%.
- Runway Left: Self-explanatory. Running off the end of the runway is not good procedure.
- Flight Time: Time which has passed in the simulation time frame. This is roughly 5 to 10 per cent of real time and depends on the time increment chosen and the operator response time.

Airborne Displays and Controls

Once the airplane is off the runway, the control messages change into two groups: cockpit display and control tower messages. These two sets of information allow the pilot to attempt level flight, turn the airplane around, and land it back on the runway.

Cockpit Display

There are fourteen flight parameters shown in the cockpit display. Some are simple reminders of control settings, while others record the aerodynamic response to these controls.

- Altitude: The airplane's altitude is given in feet. This is generally more than sufficient resolution for take off and flying. However, during the last stage of the approach for landing this increment is often not fine enough. In such a situation, the rate of descent and, more importantly, angle of attack and horizon angle are used.
- Speed: This display indicates air speed. The ground speed is not displayed and is affected by the wind. It will be observed that nosing up will usually lead to a decrease in air speed and nosing down will cause the reverse to occur. Thrust significantly affects speed.

Very high speeds can be attained in a dive. At 20% above the airplane design maximum a warning message is issued. At 40% above the maximum a wing failure abruptly occurs.

- Stall Speed: The stall speed is based on program computations using the design parameters chosen by the user at the beginning of the simulation. However, *accelerated stall* can occur in tight banks (turns). This is simulated in the program by making the stall speed an increasing function of the bank angle.
- Engine Temperature: This display gives the engine temperature in degrees Fahrenheit. Temperatures below 430°F are considered safe. Between 430°F and 450°F a warning is issued. Above 450°F the engine shuts down until it cools off. Turn on is not automatic; a thrust value (T) must be given to restart the engine. The engine temperature is calculated from the thrust used over several previous time periods. Thus it may take a while before the engine can be restarted. Needless to say, glide conditions exist in the interim.
- Fuel: The remaining weight of fuel is displayed in 1 pound increments. The rate of consumption depends on the square

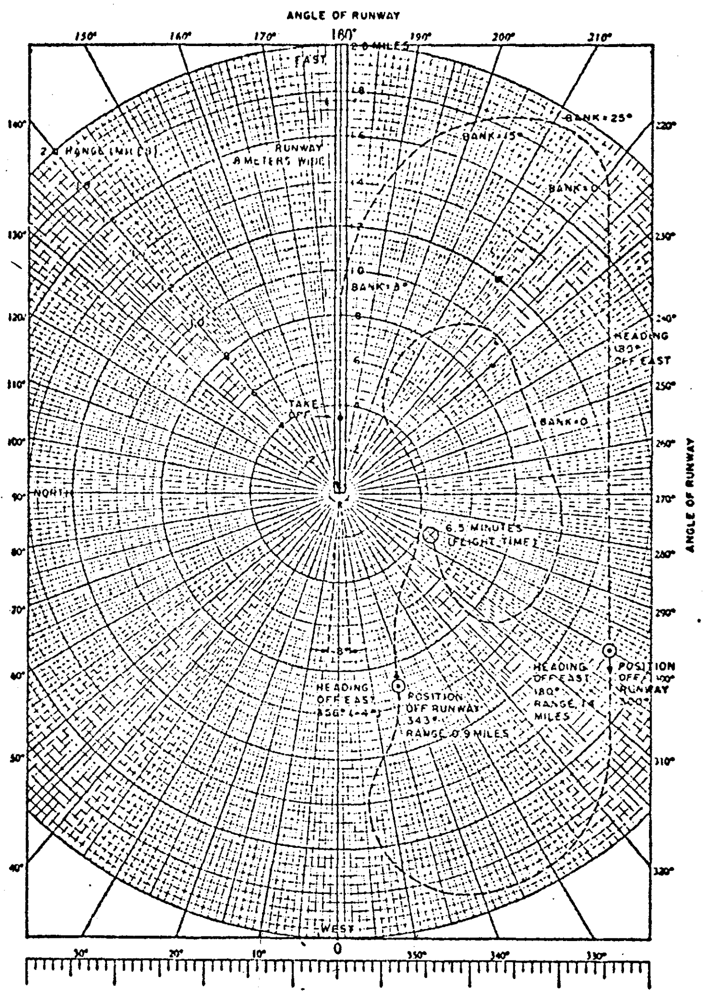

Figure 8: Polar coordinate representation of an actual computer simulation in which the course was not *plotted and carefully navigated during the flight. Subsequently, the printout was used to reconstruct the flight. Toward the west end of the runway the angular position off the runway changes rapidly, leading to confusion unless the course is continuously followed on polar coordinate paper. The coordinates and headings associated with two particular positions are shown as examples. The location convention is not difficult, but may initially be somewhat confusing to those not familiar with polar coordinate geometry.*

of the throttle (thrust) setting. Fuel consumption thus tends to be greatest during take off and climbs. The effect of fuel consumption on the overall plane weight is included.

- Flaps, Trim, Thrust, Bank: Readouts of control settings given by the pilot.
- Attack Angle: This generally corresponds in *sign* to the elevator angle. The magnitude of the response is speed dependent. A special condition exists when a critical angle of about 16° is exceeded. The attack angle pegs at that value. Unless in a dangerous landing approach situation, the attack angle (when flying upright) should be between roughly −3° and +5°. When flying inverted (yes, the simulation can handle that case also), the angle of attack should be strongly negative, say −8° or more. Observe that when flying upside down, the bank, flap, trim, and elevator controls are reversed in their flight path effects (unless you are thinking invertedly also).
- Horizon: This display gives the angle of the horizon as it would be seen from the cockpit window. It is affected by both the climb angle and the angle of attack (a linear addition). It is an important display during final approach and landing. If the horizon is lower than −6° upon touchdown, the nose gear collapses and the plane crashes. Between −6° and 0° a nose rebound occurs, bounding the plane back into the air with the nose pointed up at an angle negatively proportional to its prior horizon. Unless care is exercised in applying the controls at this point, the plane will repeatedly bounce, nose dive, or stall: A negative horizon on touchdown causes a lot of trouble.
- Heading Off East: This display indicates the instantaneous direction of travel of the craft relative to due east. This particular convention was chosen as the runway runs from west (start) to east (end). When making a final approach for landing, the heading should be near 0° (between roughly 356°, −4°, and 4° in order to hit the runway properly).
- Landing Gear, Flight Time: These are simply status displays.

Control Tower Message

It is assumed that a radar tracking control tower exists which can aid in instrument flying by giving range, speed, and meteorological information. The following information is transmitted to the pilot:

- Range: This is the radial distance in miles from the west end of the runway as illustrated in figure 8. This is a key positional display.
- Climb and Descent Rate: This is the vertical speed of the plane in increments of one foot per second. It is an important flight indicator which is particularly useful in evaluating the net response to the elevator and throttle controls. Close to touchdown, however, the resolution of this display falls short of ideal. In this case the air speed, angle of attack, and horizon indicators become the main readouts.
- Position Off Runway: This readout complements the range display. It gives the angle of the plane relative to the beginning of the runway as shown in figure 8. For example, when the airplane is on or over the runway headed due East, the angle off runway is 180°. The coordinate orientation has been chosen such that the angular position upon final approach should be near 0° or 180° depending on the approach. Also, the heading off east should be near 180° or 0°, respectively (with no wind). Quantitatively, if the heading is 180° off east at a range of 400 meters (about one quarter mile), the angular position should be between 359.4° (−0.6°) and +0.6°. This is not easy to do while also maintaining a good glide angle. Fortunately the runway is long.
- Wind, Direction, and Speed: The existence of a changeable wind sometimes makes landing a difficult chore. It largely affects the heading one must take in order to maintain an appropriate glide path. If the cross runway component of the wind exceeds six knots, the airplane may run off the side of the narrow runway if the heading just compensates for the wind at touchdown. Two alternatives exist: circling until the wind changes direction or diminishes, or changing heading just before touchdown to straighten out the airplane relative to the runway. Since the bank angle control works under the assumption of no slip, side slip is not simulated. If it were it could be used to handle the crosswind.

Cockpit Controls

There are quite a few controls which are exercised by the pilot during flight. Two, the time increment (S) and the continue character (C), have to do with the mechanics of the simulation. Once a control parameter is entered, it is latched until changed by the pilot. This is convenient once a quasi-stable flight pattern has been established. However, establishing a stable flight path is not easy. Constant control conditions may cause the airplane to rise, lose air speed and lift, nose over, dive, pick up air speed and lift and rise again. This cyclic pattern may be very extreme under some conditions.

The flight controls available in the cockpit are as follows:

- Throttle (Thrust) (T): This is the fraction of maximum thrust available, the maximum having been established in the program initialization. The entered value should be between zero and one for positive thrust, or a negative one and zero for negative thrust.
- Bank Angle (B): This puts the airplane into a no slip bank (centrifugal force perpendicular to wings). A value of 180° will invert the craft; 360° will complete the roll. Absolute values greater than 360° are not allowed. Vertical lift is lost during a bank according to the cosine of the bank angle. Stall speed also increases as the turn becomes tighter. During a tight turn, the airplane will generally lose altitude even though the nose may be on the horizon. In such a situation, increased throttle and raising the nose above the horizon helps.
- Elevators (Attack Angle) (E): As mentioned earlier, this affects the angle of the airplane's wings relative to its trajectory (ie: the attack angle). The response is speed dependent. If an attempt is made to exceed an absolute attack angle of 16° a significant loss in lift results due to turbulence in the air flow over the wings. In effect, a stall occurs. Attack angles over 10° should be avoided.

  As noted earlier, the attack angle response to the elevator control is air speed dependent. In a dive, as the air speed increase, so does the attack angle response, thus increasing lift and reducing the dive. In a climb, as the air speed decreases, the reverse happens. Thus there is some self-compensation built into the control.
- Flaps (F): Explained earlier. Once in flight, the flaps should be set to 0° to reduce drag.
- Trim (R): As far as the program is concerned, trim has an effect proportional to flaps: positive trim increases lift and negative trim decreases lift. In flight, the trim is adjusted to somewhere between −10° to +10° to give neutral elevator controls (ie: E set to zero gives level flight) at the chosen cruise speed and altitude. As fuel is consumed the craft will tend to rise; "trimming" will counter this. Many pilots enjoy continuously trimming their craft; it replaces nail biting.

  The trim value set by the Initialization is −10°. During take off this can not be altered. Once in the air the trim angle may be set to zero. However, the change should be made slowly to maintain control over the plane. Rapid changes lead to over control and erratic flight.
- Landing Gear (G): An input value for G of one lowers the landing gear. Setting G to zero raises the gear. The simulated airplane has an automatic warning system which acts when the airplane is descending and is below an altitude of approximately one hundred feet. After a long flight it is not unusual to forget to lower the landing gear. This should be checked perhaps a quarter mile from touchdown so that there is time for compensation for landing gear (aerodynamic) drag.

Touchdown Conditions

Landing on the runway is a very exacting exercise since several criteria must be satisfied.

First, the landing gear must be down. Next, the airplane must be within four meters of the runway centerline. Though the runway is long, it is also narrow. The airplane must obviously also be *on* the runway (not short or long). The horizon should be greater than −6°; 0° is very good.

The quality of the touchdown is finally determined by the rate of descent at contact. If less than 1.6 ft/s, the landing is considered soft. If between 1.6 and 5 ft/s, the landing is rated moderate. Between 5 and 33 ft/s touchdown is declared hard and a bounce occurs. Beyond that a crash condition exists.

One of the dangers to be wary of after a bounce is subsequently nosing over into the runway. To avoid this keep the nose up and apply a little more throttle.

Once the craft has settled on the runway and deceleration has begun, a test is made to determine if the end of the runway has been reached. If so, a crash has occurred; there are no survivors if the speed on leaving the runway was greater than 20 knots.

Deceleration is simple: reverse thrust is applied by inputting a negative throttle value. If forward thrust is used instead, the program will switch to the take off routine.

Additional Surprises

In addition to these initializations and commands there are several more variables which affect the airplane's simulated performance:

- Wind Effects: The effect of wind on the airplane velocity relative to ground is modelled using a random number generator. On the average, once every ten seconds the wind direction and magnitude randomly shifts (actually, there is some correlation with the previous wind vector). The net effect is that the wind vector slowly shifts with time. This effect is most important when trying to land. In fact, under some conditions, landing may be impossible.

- Ice Storms: There is one chance in a hundred that in any particular time period an ice storm will develop. The consequence of such an occurrence is an increase in the airplane's weight by 50% due to ice on the wings. This obviously creates a problem if altitude can not be maintained at a safe throttle level and if the runway is too far away.
- Altitude: The effect of altitude on lift, drag, and engine thrust is accounted for by assuming that the air density decreases exponentially with altitude (decreases by 1/e approximately every 23000 feet). This automatically places a flight ceiling restriction on the particular simulation; it is not possible to escape the Earth. This feature is not an actual subroutine, but is part of other subroutines.

Command Structure

The pilot input command structure is simple. In the flight environment the computer supplies command prompts (?) and expects replies as follows:

```
? <command letter> <carriage return>
? <control value>    <carriage return>
```

When on the runway, inputs for the throttle, flaps, and elevators are specifically asked for.

Program Execution

It is common to see someone spend more than an hour attempting to learn how to fly (just fly; not land) the simulated airplane. The simulation is not easy to master, like many Lunar Lander type programs. Practice is required to get the feel of the flight response of the particular airplane design chosen. In addition, the response changes with altitude due to the change in air density. I have seen some sessions last more than six hours (computer time, not flight time), eventually ending in a crash. The longest flights tend to be those in which the flying option is chosen. This has initial conditions in which the airplane is flying at seven miles altitude 50 miles from the runway, heading in the wrong direction. The pilot must learn to navigate somewhat to make a proper landing.

Beginners usually discover quickly that it is not very difficult to accidently stall or, if the thrust is great enough, to loop the airplane. A tendency to loop is particularly apparent for high lift or high thrust airplane designs. Recall the balsa wood (or styrofoam) gliders of your youth; when the main wing was moved forward, the airplane had a tendency to loop and stall in a cyclic fashion. A similar situation is possible under certain conditions in this simulation.

The simulation is sufficiently complete to allow not only flying loops, but also rolling and flying upside down (if the angle of attack is sufficiently negative), and perform the aerobatics normally associated with flying.

A very simple simulation run is shown in listing 2. The take off option was chosen, with the intent being to immediately land after take off using the remaining runway, and then take off again. The flight path takes one through many flight regimes, including lift off, free flight, touchdown, and runway maneuvers.

Notes

The computer simulation presented has not been completely debugged even though it has been extensively exercised. A problem with large simulations is that a bug may go undetected for some time. To aid in fixing such problems and upgrading the simulation submodels, a variables list is given in table 1.

Although the physical description of the aerodynamics of flight is not rigorous in all its subelements, the model approximations are sufficient to simulate the general interactive characteristics of flying. This philosophy of subsystem approximation for the sake of system simulation is key to the successful modeling of many systems. Quite often it is too easy to get bogged down in the details of modeling the elements only to find that the important system features may be demonstrated using less than precise inputs. This flight simulator is one such example.

Program Notes

The simulation was encoded using a subset of North Star BASIC, Version 6 Release 2. I tried to avoid using special functions which may not be available in less advanced BASIC interpreters so that the program could be easily translated into most BASICS. The statement line widths were generally kept below 40 characters because of the printout limitations of my SWTPC PR40 matrix printer.

There are a few peculiarities of North Star BASIC which must be observed in making a translation to another BASIC.

Line Delimiter: In MITS BASIC, two or more statements can be placed on one line if they are separated by a colon. North Star BASIC uses a backslash. When listing the program using Processor Technology's VDM-1 system this results in a NEW SPEED request. The VDM-1 driver can easily be changed (see manual) so that some less troublesome character prompts a display speed change.

Strings: All strings in North Star BASIC are one dimensional and, if greater than ten characters in length, must be subscripted. This is not necessary in MITS BASIC; lines 20 through 50 may be deleted and replaced with:

```
20 DIM K(12).
```

Format: In North Star BASIC, the carriage return after a print statement can be avoided by using a comma. In MITS BASIC, a semicolon is used.

The basic operators used are fairly standard: +,–,/,*,<,=,> and ↑. The functions called are SIN, COS, SQRT, EXP, ABS and INT. The commands employed are IF-THEN, GOTO, GOSUB, RETURN, INPUT, PRINT, STOP, and REM. These capabilities are common to most BASIC interpreters. Observe that two functions are conspicuously missing: LOG and ATAN. The logarithm function is not used and the inverse tangent function is calculated in a subroutine since several BASICs, including North Star's, do not have this function.

Running the program in the form shown in listing 1 requires about 14 K bytes of program memory. Removal of all REM statements, the instruction subroutine, and the instruction string list reduces the memory requirement to about 8 K bytes. A further memory savings can be incurred if an ATAN function is used along with the commands IF-THEN-ELSE, and ON-GOTO.

Program execution is relatively fast. The majority of the time is spent printing out conditions and awaiting pilot input. The longest pause associated with actual computing (based on an IMSAI 8080 with fast memory) is less than 7 seconds. Although the program looks long and inefficient in BASIC, little would be gained by going to machine language or a compiler *unless* graphics were to be included. Graphical displays require very rapid updating routines and necessitate the use of machine language routines. A small part of the inefficiency apparent in the program is due to its user-oriented structure. All internal calculations are performed in metric units, while all IO routines use the traditional units such as knots and feet.■

Listing 1: North Star BASIC listing of the flight simulator. Comments on the program are in the accompanying text box.

```
10 REM MICROCOMPUTER FLIGHT SIMULATOR
20 REM WRITTEN BY F.R. RUCKDESCHEL
30 REM 773 JOHN GLENN BLVD.
40 REM WEBSTER, NEW YORK 14580
50 REM VERSION 4 AS OF 1900 HOURS, 3/13/78
60 DIM K(12),R$(26),S$(15),T$(9)
70 DIMC$(11),D$(18),E$(19),F$(21),G$(14)
80 DIMH$(16),I$(14),J$(20),K$(20),L$(20)
90 DIMM$(15),N$(21),O$(32),P$(14),Q$(12)
100 P2=3.14159\P3=3.28\P4=57.28
110 P5=1609\P6=.5148\G=9.8
120 PRINT "*** FLIGHT SIMULATOR ***"
130 PRINT "THIS PROGRAM SIMULATES FLYING,"
140 PRINT "LANDING AND TAKE-OFF"
150 GOSUB 5160
160  PRINT "DO YOU WISH TO FLY (TYPE 1)"
170  PRINT "OR TAKE-OFF (TYPE 0):",
180 T9=0
190 T4=0\V=0\S1=0
200  INPUT Z
210  IF Z=1 THEN GOTO 240
220 IF Z=0 THEN GOTO 500
230 IF Z<>1 THEN GOTO 160
240 GOSUB 750
250 REM FLIGHT CHARACTERISTICS INPUT
260 GOSUB 930
270 REM INITIAL FLIGHT CONDITIONS
280 GOSUB 650
290 REM STALL SPEED CALC.
300 GOSUB 1180
310 REM CALC. OF CONSTANTS
320 IF X3<0 THEN X3=0
330 GOSUB 1810
340 REM COCKPIT DISPLAY
350 GOSUB 2950
360 REM CONTROL TOWER
370 GOTO 3520
380 REM TOUCHDOWN TEST
390 IF X3=0 THEN GOTO 4150
400 REM RUNWAY MANEUVERS
410 GOSUB 3180
420 REM PILOT INPUT
430 GOSUB 2390
440 REM ENGINE TEMP ROUTINE
450 IF T1>=16/P4 THEN GOSUB 2580
460 GOSUB 1420
470 REM NEW VELOCITY CALCULATION
480 GOTO 320
490 REM **********************
500 REM TAKE-OFF EXECUTIVE
510 GOSUB 4450\GOSUB 750
520 REM FLIGHT CHARACTERISTICS INPUT
530 GOSUB 650
540 REM STALL SPEED CALC.
550 GOSUB 1180
560 REM CALC. OF CONSTANTS
570 PRINT\PRINT\PRINT
580 PRINT "READY FOR TAKE-OFF"
590 GOSUB 4500
600 REM TAKE OFF ROUTINE
610 IF L<M*G THEN GOTO 590
620 PRINT "YOU ARE IN THE AIR"
630 GOTO 320
640 REM **********************
650 REM STALL SPEED CALC.
660 REM F=FLAPS
670 REM V1=MAX. SPEED
680 REM T2=GLIDE ANGLE
690 REM N1=THRUST RATIO
700 REM V2=STALL SPEED
710 V2=V1*SIN(T2)/(2*N1)
720 V2=V2*(1+0.3*ABS(SIN(B)))
730 V2=V2*SQRT(1.5/(1.0+F/2))\RETURN
740 REM **********************
750 REM FLIGHT CHARACTERISTICS
760 PRINT"INPUT THE FOLLOWING"
770 PRINT "MASS(TONS): ",\INPUT M
780 PRINT"FUEL (TONS): ",\INPUT F9
790 PRINT"THRUST FRACTION: ",\INPUT N1
800 N1=1.25*N1
810 PRINT "MAX SPEED(KNOTS): ",
820 INPUT V1
830 PRINT"GLIDE ANGLE(DEGREES):",
840 INPUT T2\T2=ABS(T2)
850 PRINT"TIME INCR.(SEC):",\INPUT T3
860 M=M*907\V1=V1*P6\T2=T2/P4
870 F9=F9*907
880 M9=M\M=M9+F9
890 PRINT\PRINT
900 PRINT"READY FOR FLIGHT"
910 PRINT\PRINT\PRINT\RETURN
920 REM **********************
930 REM INITIAL FLIGHT CONDITIONS
940 REM X1,X2 AND X3 ARE POSITIONS
950 REM S1, S2 AND S3 ARE VELOCITIES
960 REM INITIAL VELOCITY IS 3/4 MAX.
970 REM INITIAL ALTITUDE IS 7 MILES
980 X1=50.032/SQRT(2)\X2=-X1\X3=7
990 S1=.75*V1/SQRT(2)
1000 X1=X1*P5\X2=X2*P5\X3=X3*P5
1010 S2=-S1\V=0.75*V1\S3=0
1020 REM B=BANK ANGLE-
1030 REM D3=CLIMB ANGLE
1040 REM G1=LANDING GEAR
1050 REM N3=THRUST
1060 F=0\T1=0\N3=.3\B=0\T9=280\F1=0
1070 R9=-10
1080 REM T1=ANGLE OF ATTACK
1090 N2=0\D3=0\G1=0\RETURN
1100 REM **********************
1110 REM STALL PENALTY
1120 REM PLANE LOSES LIFT
1130 FOR J=1 TO 6
1140 L=L*V/V2
1150 NEXT J
1160 RETURN
1170 REM **********************
1180 REM CALC. OF CONSTANTS
1190 REM G=GRAVITATIONAL ACCELERATION
1200 REM C1=FRICTIONAL DRAG COEF.
1210 C1=N1*M*G/V1
1220 REM C2=INDUCED DRAG COEF.
1230 C2=C1*(V2^3)/((M*G*COS(T2))^2)
1240 REM C3=LIFT COEF.
1250 C3=M*G*COS(T2)
1260 C3=C3/((V2*V2*(1.0+5*16/P4)))
1270 C3=1.5*C3
1280 RETURN
1290 REM **********************
1300 REM LIFT AND DRAG CALCULATIONS
1310 REM L=LIFT  D=DRAG
1320 P1=EXP(-X3/7000)
1330 IF V=0 THEN V=0.0000001
1340 L=C3*(1.+F/2)*(1.0+5*T1)*V*V
1350 L=L*P1*(1-1/(1+(V-V2)*(V-V2)))
1360 IF V<V2 THEN GOSUB 1110
1370 REM LANDING GEAR (G1) ADDED TO DRAG
1380 D=C2*L*L/(P1*V*V)+C1*V*(1+.6*G1)*P1
1390 GOSUB 650
1400 RETURN
1410 REM **********************
1420 REM NEW VELOCITY CALCULATION
1430 REM FOUR POINT INTEGRATION
1440 T3=T3/4
1450 I=0
1460 I=I+1
1470 GOSUB 1300\GOSUB 1670\GOSUB 1730
1480 Z=N1*N3*M*G*COS(T1)*P1
1490 Z=Z-M*G*SIN(D3)-D
1500 Y=L*SIN(B)/COS(D3)
1510 W=T3/(M*V)
1520 S1=S1+W*(Z*S1-Y*S2)
1530 S2=S2+W*(Z*S2+Y*S1)
1540 S3=V*SIN(D3)
1550 V=SQRT(S1*S1+S2*S2+S3*S3)
1560 X1=X1+S1*T3\X2=X2+S2*T3
1570 X3=X3+S3*T3
1580 IF X3<0 THEN I=4
1590 IF I<4 THEN GOTO 1460
1600 T3=T3*4
1610 REM WIND EFFECTS
1620 GOSUB 5070
1630 X1=X1+S4*T3
1640 X2=X2+S5*T3
1650 RETURN
1660 REM **********************
1670 REM NOSE ANGLE CALCULATION
1680 REM T1=NOSE ANGLE REL. TO FLIGHT
1690 REM T1=ANGLE OF ATTACK ALSO
1700 IF ABS(T1)>16/P4 THEN GOSUB 2580
1710 RETURN
1720 REM **********************
1730 REM CLIMB ANGLE CALCULATION
1740 T7=N1*N3*G*SIN(T1)/V
1750 T7=T7-G*COS(D3)/V+L*COS(B)/(M*V)
1760 D3=D3+T3*T7
1770 IF D3>P2 THEN D3=D3-P2
1780 IF D3<-P2 THEN D3=D3+P2
1790 RETURN
1800 REM **********************
1810 REM COCKPIT DISPLAY
1820 PRINT O$\PRINT\PRINT
1830 PRINT"ALT.: ",INT(X3*P3)," FEET"
1840 PRINT"SPEED: ",INT(V/P6)," KNOTS"
1850 GOSUB 650
1860 REM STALL SPEED CALC.
1870 IF V>=V2 THEN GOTO 1910
1880 PRINT\PRINT O$
1890 PRINT\PRINT "***STALL***"
1900 PRINT\PRINT O$
1910 PRINT"STALL SPEED: ",
1920 PRINT INT(V2/P6),
1930 PRINT " KNOTS"
1940 PRINT"ENGINE TEMP: ",INT(T9)," DEG"
1950 GOSUB 2320
1960 PRINT"FUEL",INT(2.2*F9)," LBS."
1970 PRINT "FLAPS: ",INT(100*F1)/100,
1980 PRINT " DEGREES"
1990 PRINT "TRIM: ",INT(R9*100)/100,
2000 PRINT " DEGREES"
2010 PRINT "THRUST: ",INT(100*N3)/100
2020 PRINT "BANK: ",INT(B*572.8)/10,
2030 PRINT " DEGREES"
2040 PRINT "ATTACK ANGLE: ",
2050 PRINT INT(T1*P4*10)/10,
2060 PRINT " DEGREES"
2070 PRINT"HORIZON: ",
2080 PRINT INT(10*(D3+T1)*P4)/10,
2090 PRINT " DEGREES"
2100 PRINT "HEADING OFF EAST: ",
2110 M1=S1\M2=-S2
2120 GOSUB 2720
2130 GOSUB 2230
2140 PRINT "LANDING GEAR: ",
2150 IF G1=0 THEN PRINT " UP"
2160 IF G1=1 THEN PRINT " DOWN"
2170 T4=T4+T3
2180 PRINT "FLIGHT TIME: ",
2190 PRINT INT(10*T4/6)/100," MIN."
2200 GOSUB 4970
2210 GOSUB 2630\RETURN
2220 REM **********************
2230 REM DIVE SPEED TEST
2240 IF V<1.2*V1 THEN RETURN
2250 PRINT\PRINT O$
2260 PRINT S$\PRINT O$\PRINT
2270 IF V<1.4*V1 THEN RETURN
2280 PRINT\PRINT T$\PRINT F$
2290 PRINT C$\PRINT D$
2300 GOTO 5830
2310 REM **********************
2320 REM FUEL CONSUMPTION SUBROUTINE
2330 F9=F9-T3*(N3*2)*(N3*2)*M9/200000
2340 IF F9<0 THEN F9=0
2350 IF F9=0 THEN T=0
2360 M=M9+F9
2370 RETURN
2380 REM **********************
2390 REM ENGINE TEMPERATURE
2400 FOR I=1 TO 8\K(I)=K(I+1)\NEXT I
2410 K(9)=N3\T9=0\FOR I=2 TO 9
2420 T9=T9+K(I)*(I-1)*3.2\NEXT I
2430 T9=T9+340
2440 T9=T9*(1+P1)/2\IF T9<75 THEN T9=75
2450 IF T9<430 THEN GOTO 2500
2460 IF T9>=450 THEN GOSUB 2520
2470 IF T9<450 THEN PRINT
2480 IF T9<450 THEN PRINT "*ENGINE*"
2490 IF  T9<450 THEN PRINT"***HOT***"
2500 RETURN
2510 REM **********************
2520 REM ENGINE WARNING
2530 PRINT
2540 PRINT "***ENGINE OVERHEAT***"
2550 PRINT"POWER OFF"\PRINT
2560 N3=0\RETURN
2570 REM **********************
2580 REM ATTACK ANGLE PASS CRITICAL
2590 FOR J=1 TO 4
2600 L=L*16/(P4*T1)
2610 NEXT I\RETURN
2620 REM **********************
2630 REM LANDING GEAR WARNING
2640 IF G1=1 THEN RETURN
2650 IF X3>30 THEN RETURN
2660 PRINT\PRINT
2670 IF D3>0 THEN RETURN
2680 PRINT "***WARNING***"
2690 PRINT "LANDING WITH GEAR UP"
2700 RETURN
2710 REM **********************
2720 REM INVERSE TANGENT
2730 REM APPROXIMATIONS FOR DIGITAL
2740 REM COMPUTERS
2750 REM BY CECIL HASTINGS,JR.
2760 REM PRINCETON UNIVERSITY PRESS
2770 L4=(0.0000001)^3
2780 IF ABS(M2)<L4 THEN M2=2*L4
2790 IF ABS(M1)<L4 THEN M1=2*L4
2800 X=M2/M1
2810 IF ABS(X+1)<L4 THEN X=L4-1
2820 IF X<0 THEN X=-X
2830 X=(X-1)/(X+1)\L1=.995354
2840 L2=-.288679\L3=.079331
2850 U2=3.14159/4+L1*X+L2*(X^3)+L3*(X^5)
2860 IF M1>0 THEN GOTO 2900
2870 IF M2>0 THEN U2=P2-U2
2880 IF M2<0 THEN U2=P2+U2
2890 GOTO 2920
2900 IF M2>0 THEN U2=U2
2910 IF M2<0 THEN U2=2*P2-U2
2920 PRINT INT(U2*572.8+.5)/10," DEG."
2930 RETURN
2940 REM **********************
2950 REM CONTROL TOWER
2960 PRINT\PRINT
2970 PRINT "CONTROL TOWER MESSAGE"
2980 PRINT O$
2990 R=SQRT(X1*X1+X2*X2)
3000 PRINT "RANGE: ",INT(R/16.1)/100,
3010 PRINT " MILES"
3020 P$="DESCENT RATE: "
3030 Q$="CLIMB RATE: "
3040 IF S3<0 THEN PRINT P$,
3050 IF S3>=0 THEN PRINT Q$,
3060 PRINT INT(ABS(S3)*P3),
3070 PRINT " FEET/SEC"\M2=-X2\M1=-X1
3080 PRINT "POSITION OFF RUNWAY: ",
3090 GOSUB 2720
3100 PRINT "WIND DIRECTION: ",
3110 M1=S4\M2=-S5
3120 GOSUB 2720
3130 PRINT "WIND SPEED: ",
3140 PRINT INT(SQRT(S4*S4+S5*S5)/16),
3150 PRINT " KNOTS"
3160 RETURN
3170 REM **********************
3180 REM COCKPIT CONTROL
3190 PRINT\PRINT
3200 PRINT "COCKPIT CONTROL",
3210 INPUT B$
3220 REM C=CONTINUE
3230 IF B$<>"C" THEN INPUT Y1
3240 IF B$="C" THEN RETURN
3250 REM T=THROTTLE OR THRUST
3260 IF B$="T" THEN N3=Y1
3270 IF N3>1 THEN PRINT M$
3280 IF N3>1 THEN N3=1
3290 REM B=BANK ANGLE
3300 IF B$="B" THEN B=Y1
3310 IF ABS(B)>=360 THEN PRINT R$
3320 IF ABS(B)>=360 THEN GOTO 3300
3330 IF B$="B" THEN B=B/P4
3340 REM E=ELEVATORS
3350 IF B$="E" THEN T1=(Y1/P4)*(V/V1)
3360 REM S=SECONDS
3370 IF B$="S" THEN T3=Y1
3380 REM F=FLAPS
3390 IF B$="F" THEN F1=Y1
3400 IF F1<0 THEN GOTO 3210
3410 IF F1>45 THEN F1=45*ABS(F1)/F1
3420 REM R=TRIM
3430 IF B$="R" THEN R9=Y1
3440 IF ABS(R9)>10 THEN R9=10*ABS(R9)/R9
3450 F=(F1+3*R9)/75
3460 REM G=LANDING GEAR
3470 IF B$="G" THEN G1=Y1
3480 IF G1>0 THEN G1=1
3490 IF G1<=0 THEN G1=0
3500 PRINT\PRINT\GOTO 3210
3510 REM **********************
3520 REM TOUCHDOWN
3530 IF X3>0 THEN GOTO 390
3540 X3=0
3550 IF G1=1 THEN GOTO 3610
3560 PRINT\PRINT\PRINT
3570 PRINT C$
3580 PRINT "LANDED WITH GEAR UP"
3590 PRINT D$
3600 GOTO 5830
3610 IF ABS(X2)<4 THEN GOTO 3650
3620 PRINT\PRINT\PRINT C$
3630 PRINT E$\PRINT D$\GOTO 5830
3640 PRINT D$\GOTO 5830
3650 IF X1<0 THEN GOTO 3620
3660 IF X1>2*5280/3.28 THEN GOTO 3620
3670 IF (D3+T1)*P4>0 THEN GOTO 3870
3680 IF (D3+T1)*P4>-6 THEN GOTO 3740
3690 PRINT\PRINT O$
3700 PRINT C$
3710 PRINT F$
3720 PRINT D$
3730 GOTO 5830
3740 PRINT\PRINT O$\PRINT
3750 PRINT "NOSE WHEEL HIT FIRST"
3760 PRINT
3770 D3=-D3/2
3780 S3=D3*V/2
3790 V=0.9*V
3800 X3=S3*T3
3810 PRINT "***BOUNCE***"
3820 PRINT\PRINT "ALTITUDE: ",
3830 PRINT INT(X3*P3)," FEET"
3840 PRINT "CLIMB ANGLE: ",INT(10*D3*P4)/10,
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3850 PRINT " DEGREES"
3860 GOTO 410
3870 IF ABS(S2)>3 THEN GOTO 3620
3880 PRINT\PRINT\PRINT
3890 PRINT "**********************"
3900 PRINT "***TOUCHDOWN****"
3910 PRINT
3920 IF S3>-.5 THEN PRINT G$
3930 IF S3>-.5 THEN GOTO 4010
3940 IF S3>-1.5 THEN PRINT H$
3950 IF S3>-1.5 THEN GOTO 4010
3960 IF S3>-10 THEN PRINT I$
3970 IF S3>-10 THEN GOTO 4010
3980 PRINT\PRINT\PRINT
3990 PRINT C$\PRINT I$\PRINT F$
4000 PRINT D$
4010 PRINT\PRINT
4020 REM RUNWAY BOUNCE TEST
4030 IF S3>-1.5 THEN GOTO 4130
4040 PRINT "***BOUNCE****"
4050 S3=0.5*ABS(S3)
4060 D3=S3/V
4070 X3=S3*T3
4080 PRINT\PRINT "ALTITUDE: ";
4090 PRINT INT(X3*P3)," FEET"
4100 PRINT "CLIMB ANGLE: ",INT(10*D3*P4)/10
4110 PRINT " DEGREES"
4120 GOTO 410
4130 GOTO 390
4140 **************************
4150 REM RUNWAY MANEUVERS
4160 R2=10560-P3*X1
4170 IF R2>0 THEN GOTO 4220
4180 PRINT\PRINT\PRINT C$\PRINT N$
4190 IF S1<10 THEN PRINT L$
4200 IF S1>10 THEN PRINT D$
4210 IF S1>10 THEN GOTO 5830
4220 PRINT "RUNWAY SPEED: ",
4230 PRINT INT(S1/P6  )," KNOTS"
4240 PRINT INT(R2),K$
4250 PRINT"THRUST:",\INPUT N3
4260 IF ABS(N3)>1 THEN PRINT M$
4270 IF ABS(N3)>1 THEN GOTO 4250
4280 IF N3>0 THEN GOTO 590
4290 REM SWITCH TO TAKE-OFF ROUTINE
4300 N3=N3/2
4310 REM FUEL CALC.
4320 GOSUB 2320
4330 GOSUB 1300
4340 S1=S1+(N3*N1*G-ABS(D/M))*T3
4350 V=ABS(S1)
4360 X1=X1+S1*T3
4370 PRINT "LIFT (%): ",
4380 GOSUB 1300
4390 PRINT INT(100*L/(M*G))
4400 IF L>M*G THEN GOTO 620
4410 IF ABS(S1)>1/3.28 THEN GOTO 4160
4420 PRINT "LANDING COMPLETE"
4430 PRINT INT(R2),K$\GOTO 5830
4440 REM **********************
4450 REM TAKE-OFF INITIALIZATION
4460 X1=0\X2=0\X3=0\S1=0\S2=0\S3=0
4470 F=0\G1=1\N3=0\D3=0\N2=0\R9=-10
4480 T9=300\T1=0\RETURN
4490 REM **********************
4500 REM TAKE-OFF ROUTINE
4510 PRINT "THRUST: ",\INPUT N3
4520 IF ABS(N3)>1 THEN PRINT M$
4530 IF ABS(N3)>1 THEN GOTO 4510
4540 REM FUEL CALC.
4550 GOSUB 2320
4560 REM ENGINE TEMP CALC.
4570 GOSUB 2390
4580 PRINT "FLAPS: ",\INPUT F1
4590 IF F1<0 THEN GOTO 4580
4600 IF ABS(F1)>45 THEN F1=45*ABS(F1)/F1
4610 F=(F1+3*R9)/75
4620 PRINT "ELEVATOR DEGREES: ",\INPUT T1
4630 IF ABS(T1)>45 THEN GOTO 4620
4640 T1=T1/P4\T1=(V/V1)*T1
4650 PRINT\PRINT O$
4660 PRINT "HORIZON: ",INT(T1*P4*10)/10
4670 REM FOUR POINT INTEGRATION
4680 T3=T3/4
4690 FOR I=1 TO 4
4700 GOSUB 1300
4710 S1=S1+(N3*N1*G-D/M)*T3
4720 V=S1\X1=X1+S1*T3
4730 NEXT I\T3=T3*4
4740 PRINT "RUNWAY SPEED: ",
4750 PRINT INT(S1/P6)," KNOTS"
4760 GOSUB 650
4770 PRINT "STALL SPEED: ",
4780 PRINT INT(V2/P6)," KNOTS"
4790 REM LIFT AND DRAG CALC.
4800 GOSUB 650
4810 PRINT "LIFT (%): ",
4820 PRINT INT(100*L/(M*G))
4830 R2=10560-P3*X1
4840 IF R2>0 THEN GOTO 4870
4850 PRINT\PRINT\PRINT C$\PRINT N$
4860 PRINT D$\GOSUB 5830
4870 PRINT INT(R2),K$\T4=T4+T3
4880 PRINT "FLIGHT TIME: ",INT(T4),
4890 PRINT " SECONDS"
4900 PRINT O$\PRINT
4910 IF L<M*G THEN RETURN
4920 PRINT\PRINT\PRINT
4930 PRINT "***LIFT OFF****"
4940 D3=0.1*V/V1\X3=D3*V
4950 S3=T3*(L-M*G)/M
4960 RETURN
4970 REM **********************
4980 REM ICE STORM
4990 IF RND(ABS(V/V1)/2)>.01 THEN RETURN
5000 M9=2.0*M9
5010 PRINT\PRINT
5020 PRINT"****DANGER****"
5030 PRINT"SLEET STORM"
5040 PRINT"WINGS ICING UP!!!"
5050 RETURN
5060 REM ********************
5070 REM WIND EFFECTS
5080 B9=ABS((V/V1)/3)
5090 C9=ABS((V/V1)/4)
5100 B9=RND(B9)\C9=RND(C9)
5110 IF B9>.1 THEN RETURN
5120 S4=(4*(B9-.05)*V+S4)/2
5130 IF C9>.1 THEN RETURN
5140 S5=(4*(C9-.05)*V+S5)/2\RETURN
5150 REM **********************
5160 REM MESSAGE LIST
5170 C$="***CRASH****"
5180 D$="***NO SURVIVORS****"
5190 E$="***MISSED RUNWAY****"
5200 F$="***LOSS OF CONTROL****"
5210 G$="TOUCHDOWN SOFT"
5220 H$="TOUCHDOWN MEDIUM"
5230 I$="TOUCHDOWN HARD"
5240 K$=" FEET OF RUNWAY LEFT"
5250 N$="RAN OFF END OF RUNWAY"
5260 L$="DAMAGE TO PLANE ONLY"
5270 M$="MAX. THRUST = 1"
5280 O$="**********************************"
5290 R$="MAX. ROLL IS 360 DEGREES"
5300 S$="DANGEROUS DIVE"
5310 T$="LOST WING"
5320 PRINT\PRINT O$\PRINT
5330 PRINT"***BASIC INSTRUCTIONS****"
5340 PRINT"DO YOU WISH INSTRUCTIONS?",
5350 PRINT" (Y/N): ",\INPUT B$
5360 IF B$="N" THEN RETURN
5370 PRINT\PRINT
5380 PRINT"THERE ARE TWO INITIAL FLIGH",
5390 PRINT"T CONDITIONS. ONE STARTS T",
5400 PRINT"HE PLANE 50 MILES FROM THE",
5410 PRINT" AIRPORT AT AN ALTITUDE OF",
5420 PRINT" SEVEN MILES. THE OTHER ST",
5430 PRINT"ARTS ON THE RUNWAY. THE FL",
5440 PRINT"IGHT CHARACTERISTICS OF TH",
5450 PRINT"E PLANE ARE DEFINED BY THE",
5460 PRINT" USER. THEY ARE:"
5470 PRINT"   MASS OF THE PLANE"
5480 PRINT"   THRUST AS A FRACTION"
5490 PRINT"   OF THE PLANE WEIGHT"
5500 PRINT"   MAX. LEVEL FLIGHT SPEED"
5510 PRINT"   GLIDE ANGLE AT STALL"
5520 PRINT"   ELEVATOR COEF. (NOSE)"
5530 PRINT"   TIME INCREMENT"
5540 PRINT\PRINT\PRINT"THERE ARE TWO ",
5550 PRINT"MESSAGE SETS. ONE IS A COC",
5560 PRINT"KPIT DISPLAY WHICH IS SELF ",
5570 PRINT"EXPLANATORY. THE OTHER IS ",
5580 PRINT"A CONTROL TOWER MESSAGE GI",
5590 PRINT"VING RANGE, DESCENT RATE A",
5600 PRINT"ND POSITION RELATIVE TO TH",
5610 PRINT"E RUNWAY. THE FLIGHT CONTR",
5620 PRINT"OL FUNCTIONS ARE:"
5630 PRINT"   C=CONTINUE WITH SAME"
5640 PRINT"   T=FRACTION OF MAX THRUST"
5650 PRINT"   B=BANK ANGLE IN DEGREES"
5660 PRINT"   E=ELEVATOR (DEGREES)"
5670 PRINT"   F=FLAPS (0 TO 45 DEG.)"
5680 PRINT"   R=TRIM (DEGREES)"
5690 PRINT"   G=LANDING GEAR(0 UP/1 DN)"
5700 PRINT"   S=NEW TIME INCREMENT"
5710 PRINT\PRINT"IT IS SUGGESTED THAT",
5720 PRINT" THE TAKE OFF OPTION BE FI",
5730 PRINT"RST CHOSEN FOR EXPERIENCE.",
5740 PRINT" A GOOD STARTING TIME INCR",
5750 PRINT"EMENT IS THREE SECS. A REA",
5760 PRINT"SONABLE STARTING PLANE WOU",
5770 PRINT"LD BE 1 TON, FUEL .3 TONS,",
5780 PRINT" THRUST OF .3, A MAX SPEED",
5790 PRINT" OF 180 KNOTS, GLIDE ANGLE",
5800 PRINT" OF 11 DEGREES. GOOD LUCK."
5810 RETURN
5820 REM **********************
5830 REM FINAL STATUS
5840 PRINT\PRINT\PRINT
5850 PRINT"FINAL FLIGHT STATUS"\PRINT
5860 PRINT"TIME OF FLIGHT: ",
5870 PRINT INT(10*T4/6)/100," MIN."
5880 PRINT"FUEL LEFT: ",INT(F9*2.2),
5890 PRINT " LBS."
5900 PRINT"FINAL SPEED: ",INT(V/P6),
5910 PRINT " KNOTS"
5920 PRINT"FINAL HORIZON: ";
5930 PRINT INT((D3+T1)*P4)," DEGREES"
5940 PRINT"TRY AGAIN? (Y/N): ",
5950 INPUT B$\IF B$<>"N" THEN GOTO 160
5960 PRINT"GOODBYE. COME AGAIN SOON."
5970 END
READY
```

Table 1: This table of variables and parameter definitions will aid in updating the simulation in listing 1.

B = bank angle (radians)
B9 = random number in wind effects routine
C1 = frictional drag coefficient
C2 = induced drag coefficient
C3 = lift coefficient
C9 = random number in wind effects routine
D = drag (Newtons)
D3 = climb angle (radians)
F = total flaps, including trim (normalized; 45° = 1)
F1 = flaps
F9 = fuel supply (kilograms)
G = gravitational constant (meters/second^2)
G1 = landing gear index (0 or 1)
K(I) = thrust sequence
L = lift (newtons)
L1 = constant in ATAN routine
L2 = constant in ATAN routine
L3 = constant in ATAN routine
L4 = small constant very near zero
M = total airplane mass (kilograms)
M1 = dummy variable passed to ATAN
M2 = dummy variable passed to ATAN
M9 = initial plane (minus fuel) mass (kilograms)
N1 = maximum thrust ratio (normalized)
N3 = fraction of available power used (normalized)
P1 = air density (normalized)
P2 = π
P3 = feet to meter conversion factor
P4 = degrees to radian conversion factor
P5 = meters to mile conversion factor
P6 = (meters/second) to knots conversion factor
Q1 = elevator control (radians)
R = range of plane from runway (meters)
R2 = length of runway left (feet)
R9 = trim (radians)
S1 = eastward speed component (meters/second)
S2 = northward speed component (meters/second)
S3 = vertical speed component (meters/second)
S4 = eastward wind component (meters/second)
S5 = northward wind component (meters/second)
T1 = attack angle (radians)
T2 = glide angle (radians)
T3 = time increment (seconds)
T4 = accumulated time (seconds)
T7 = dummy variable
T9 = engine temperature (°F)
U2 = angle (radians)
V = line of flight speed (meters/second)
V1 = maximum sea level speed (meters/second)
V2 = stall speed
W = dummy variable
X = dummy variable in ATAN routine
X1 = east coordinate (meters)
X2 = north coordinate (meters)
X3 = altitude (meters)
Y = dummy variable
Y1 = dummy input variable
Z = dummy variable

Listing 2: Part of a typical session at a terminal with the simulator. Notice that the engines will begin to overheat if full throttle is applied for extended periods of time. It took several attempts to land the airplane without bouncing it. The nose must be pointed up or exactly parallel with the runway for the airplane to land safely. This output shows that even someone who has been using the simulator for some time (an experienced pilot) can have some difficulty controlling the airplane's motions.

```
RUN

*** FLIGHT SIMULATOR ***
THIS PROGRAM SIMULATES FLYING
LANDING AND TAKE-OFF

********************************

***BASIC INSTRUCTIONS***
DO YOU WISH INSTRUCTIONS? (Y/N): ?N
DO YOU WISH TO FLY (TYPE 1)
OR TAKE-OFF (TYPE 0):?0
INPUT THE FOLLOWING
MASS(TONS): ?1
FUEL (TONS): ?.3
THRUST FRACTION: ?.3
MAX SPEED(KNOTS): ?180
GLIDE ANGLE(DEGREES):?31
TIME INCR.(SEC):?3


READY FOR FLIGHT




READY FOR TAKE-OFF
THRUST: ?1
FLAPS: ?0
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  20 KNOTS
STALL SPEED:  61 KNOTS
LIFT ($):  0
 10498 FEET OF RUNWAY LEFT
FLIGHT TIME:  3 SECONDS
********************************

THRUST: ?1
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  37 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  1
 10336 FEET OF RUNWAY LEFT
FLIGHT TIME:  6 SECONDS
********************************

THRUST: ?1
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  51 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  29
 10099 FEET OF RUNWAY LEFT
FLIGHT TIME:  9 SECONDS
********************************

THRUST: ?1
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  61 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  76
 9804 FEET OF RUNWAY LEFT
FLIGHT TIME:  12 SECONDS
********************************

THRUST: ?1

*ENGINE*
***HOT***
FLAPS: ?25
ELEVATOR DEGREES: ?8

********************************
HORIZON:  2.7
RUNWAY SPEED:  66 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  116
 9475 FEET OF RUNWAY LEFT
FLIGHT TIME:  15 SECONDS
********************************

***LIFT OFF***
YOU ARE IN THE AIR
********************************


ALT :  4 FEET
SPEED:  66 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  435 DEG
FUEL 591 LBS.
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  1
BANK:  0 DEGREES
ATTACK ANGLE:  2.7 DEGREES
HORIZON:  4.8 DEGREES
HEADING OFF EAST:  0 DEG
LANDING GEAR:  DOWN
FLIGHT TIME:  .3 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .2 MILES
CLIMB RATE:  15 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  45 DEG
WIND SPEED:  0 KNOTS


COCKPIT CONTROL?T
?.7


?E
?0


?C

*ENGINE*
***HOT***
********************************


ALT :  9 FEET
SPEED:  66 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  437 DEG
FUEL 590 LBS.
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .7
BANK:  0 DEGREES
ATTACK ANGLE:  0 DEGREES
HORIZON:  -.1 DEGREES
HEADING OFF EAST:  0 DEG.
LANDING GEAR:  DOWN
FLIGHT TIME:  .35 MIN


CONTROL TOWER MESSAGE
********************************
RANGE:  .26 MILES
DESCENT RATE:  0 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG
WIND SPEED:  0 KNOTS


COCKPIT CONTROL?E
?.7


?T
?.6


?C

*ENGINE*
***HOT***
********************************


ALT :  7 FEET
SPEED:  64 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  434 DEG
FUEL 590 LBS
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .6
BANK:  0 DEGREES
ATTACK ANGLE:  .6 DEGREES
HORIZON:  - 2 DEGREES
HEADING OFF EAST:  0 DEG.
LANDING GEAR:  DOWN
FLIGHT TIME:   4 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .33 MILES
DESCENT RATE:  1 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS


COCKPIT CONTROL?E
?.8


?C

*ENGINE*
***HOT***
********************************


ALT.:  0 FEET
SPEED:  64 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  430 DEG
FUEL 589 LBS
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .6
BANK:  0 DEGREES
ATTACK ANGLE:  .7 DEGREES
HORIZON:  -1.7 DEGREES
HEADING OFF EAST:  0 DEG
LANDING GEAR:  DOWN
FLIGHT TIME:  .45 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .37 MILES
DESCENT RATE:  4 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG
WIND SPEED:  0 KNOTS

********************************

NOSE WHEEL HIT FIRST

***BOUNCE***

ALTITUDE:  3 FEET
CLIMB ANGLE:  1.2 DEGREES


COCKPIT CONTROL?E
?2


?C
********************************

ALT.:  3 FEET
SPEED:  61 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  423 DEG
FUEL 589 LBS
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .6
BANK:  0 DEGREES
ATTACK ANGLE:  2 DEGREES
HORIZON:  2.5 DEGREES
HEADING OFF EAST:  0 DEG.
LANDING GEAR:  DOWN
FLIGHT TIME:  .5 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .44 MILES
CLIMB RATE:  1 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS


COCKPIT CONTROL?T
?.5


?C
********************************


ALT :  0 FEET
SPEED:  59 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  415 DEG
FUEL 589 LBS
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .5
BANK:  0 DEGREES
ATTACK ANGLE:  2 DEGREES
HORIZON:  -.8 DEGREES
HEADING OFF EAST:  0 DEG.
LANDING GEAR:  DOWN
FLIGHT TIME:  .55 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .49 MILES
DESCENT RATE:  4 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS

********************************

NOSE WHEEL HIT FIRST

***BOUNCE***

ALTITUDE:  3 FEET
CLIMB ANGLE:  1.3 DEGREES


COCKPIT CONTROL?E
?2.5


?C
********************************


ALT :  0 FEET
SPEED:  59 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  409 DEG
FUEL 588 LBS.
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .5
BANK:  0 DEGREES
ATTACK ANGLE:  2.5 DEGREES
HORIZON:  -.7 DEGREES
HEADING OFF EAST:  0 DEG.
LANDING GEAR:  DOWN
FLIGHT TIME:  .6 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .52 MILES
DESCENT RATE:  5 FEET/SEC
POSITION OFF RUNWAY:  180 DEG.
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS

********************************

NOSE WHEEL HIT FIRST

***BOUNCE***

ALTITUDE:  4 FEET
CLIMB ANGLE:  1.5 DEGREES


COCKPIT CONTROL?E
?3


?C
********************************


ALT :  0 FEET
SPEED:  58 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  404 DEG
FUEL 588 LBS
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  .5
BANK:  0 DEGREES
```

```
ATTACK ANGLE:  3 DEGREES
HORIZON:  .7 DEGREES
HEADING OFF EAST:  0 DEG
FLIGHT TIME:  .65 MIN

CONTROL TOWER MESSAGE
********************************
RANGE:  .55 MILES
DESCENT RATE:  3 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS


********************
***TOUCHDOWN***

TOUCHDOWN MEDIUM


RUNWAY SPEED:  58 KNOTS
 7624 FEET OF RUNWAY LEFT
THRUST:?0
LIFT ($):  15
RUNWAY SPEED:  43 KNOTS
 7402 FEET OF RUNWAY LEFT
THRUST:?0
LIFT ($):  3
RUNWAY SPEED:  36 KNOTS
 7216 FEET OF RUNWAY LEFT
THRUST:?-1
LIFT ($):  0
RUNWAY SPEED:  20 KNOTS
 7114 FEET OF RUNWAY LEFT
THRUST:?-1
LIFT ($):  0
RUNWAY SPEED:  6 KNOTS
 7032 FEET OF RUNWAY LEFT
THRUST:?1
THRUST: ?1
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  25 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  0
 6987 FEET OF RUNWAY LEFT
FLIGHT TIME:  42 SECONDS
********************************

THRUST: ?1
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  42 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  4
 6804 FEET OF RUNWAY LEFT
FLIGHT TIME:  45 SECONDS
********************************

THRUST: ?1

*ENGINE*
***HOT***
FLAPS: ?25
ELEVATOR DEGREES: ?0
```

```
********************************
HORIZON:  0
RUNWAY SPEED:  55 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  54
 6548 FEET OF RUNWAY LEFT
FLIGHT TIME:  49 SECONDS
********************************

THRUST: ?1

*ENGINE*
***HOT***
FLAPS: ?25
ELEVATOR DEGREES: ?0

********************************
HORIZON:  0
RUNWAY SPEED:  63 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  83
 6240 FEET OF RUNWAY LEFT
FLIGHT TIME:  51 SECONDS
********************************

THRUST: ?1

*ENGINE*
***HOT***
FLAPS: ?25
ELEVATOR DEGREES: ?8

********************************
HORIZON:  2.8
RUNWAY SPEED:  68 KNOTS
STALL SPEED:  53 KNOTS
LIFT ($):  123
 5902 FEET OF RUNWAY LEFT
FLIGHT TIME:  54 SECONDS
********************************



***LIFT OFF***
YOU ARE IN THE AIR
********************************


ALT.:  4 FEET
SPEED:  68 KNOTS
STALL SPEED:  53 KNOTS
ENGINE TEMP:  445 DEG
FUEL 580 LBS.
FLAPS:  25 DEGREES
TRIM:  -5 DEGREES
THRUST:  1
BANK:  0 DEGREES
ATTACK ANGLE:  2.8 DEGREES
HORIZON:  5 DEGREES
HEADING OFF EAST:  0 DEG
LANDING GEAR:  DOWN
FLIGHT TIME:  .95 MIN.


CONTROL TOWER MESSAGE
********************************
RANGE:  .88 MILES
CLIMB RATE:  22 FEET/SEC
POSITION OFF RUNWAY:  180 DEG
WIND DIRECTION:  0 DEG.
WIND SPEED:  0 KNOTS
```