EivaN: An Interactive Orbital Trajectory Planning Tool

Adam R. Brody*
Sterling Software, Palo Alto, California 94303

EivaN is an interactive orbital trajectory planning tool that runs on a desktop computer with commercially available software. Orbital operations at any altitude around any celestial body can be planned and plotted on one's desktop with eivaN. After inputting the initial position of an object, such as an orbital maneuvering vehicle, with respect to a "stationary" object, such as a space station in a circular orbit, the operator enters the parameters of thruster firings in four dimensions (three spatial, one temporal) in order to simulate a particular mission, such as a docking maneuver. EivaN then plots the resulting trajectory. Currently, up to 5 burns may be used with 21 points plotted for each burn at a user-specified time interval. However, both the number of points and the number of burns may be modified. EivaN has successfully been used in several studies. One demonstrated the ability of naive subjects to plan docking maneuvers; the other determined velocity increment requirements for the self-rescue of a stranded extra-vehicular activity crewperson. EivaN is being used by researchers both domestic and international. NASA's computer database, COSMIC, has evaluated eivaN and is in charge of its distribution.

Introduction

BECAUSE the motions resulting from thruster activity on-orbit are nonlinear and nonintuitive, a plotting tool is necessary to aid in planning and visualizing such orbital maneuvers as rendezvous, docking, and other proximity operations (PROX OPS). Mission planners would use the device for designing trajectories and for determining fuel consumption and velocity increment levels. Students would use the tool to develop a better understanding of orbital mechanics effects. Pilots would use the tool interactively while flying a maneuver to verify their progress and monitor their performance. Such a tool would also be useful in designing contingency operations, such as retrieval of a lost piece of hardware or rescue of a stranded astronaut.

EivaN was created as the "forward-looking" counterpart to a device known as Navie.[1] Navie is a "backward-looking" tool in that the operator selects "waypoints" in space and time and Navie plots the least fuel trajectory connecting the points. With eivaN, the operator locates burn (or waypoint) magnitudes in space and time and eivaN plots the resulting trajectory. Most of the advantages of eivaN over other similar forward-looking course plotting tools are available by virtue of the application software and computer with which it runs: eivaN is inexpensive, easy to use, highly interactive, and enables variable graphical output.

EivaN consists of a spreadsheet that computes the data for the orbital trajectories, which are then presented in a graphical format. Note the following, from Ref. 3:

> A spacecraft in orbit around the earth obeys laws that fundamentally serve to balance kinetic energy and the gravitational potential. The most general form is the vis-viva equation, namely, $v^2 = \mu_E(2/r - 1/a)$ where v is the orbital velocity, μ_E is the gravitational constant, equal to 398604 km^3/s^2 for the earth, and a is the semi-major axis of the elliptical orbit. For a circular orbit, a is the radius and $v = \sqrt{(\mu/r)}$. The orbital period is $P = 2\pi\sqrt{(a^3/\mu)}$.

The equations of motion that govern the relative motion between one body in a uniform circular orbit (space station) and another body (orbiting spacecraft) are known collectively as the Clohessy-Wiltshire solutions to Hill's equations. These solutions describe relative position as a function of time... The closed forms are (Ref. 2):

$$X = V_{x0}\sin(nt)/n - (2V_{y0}/n + 3X_0)\cos(nt) + 2V_{y0}/n + 4X_0$$

$$Y = 2V_{x0}\cos(nt)/n + (4V_{y0}/n + 6X_0)\sin(nt) + (Y_0 - 2V_{x0}/n) - (3V_{y0} + 6nX_0)t$$

$$Z = Z_0\cos(nt) + V_{z0}\sin(nt)/n$$

where X is measured radially outward, Y is along the velocity vector, and Z is positive out of the orbital plane to the left. The mean orbital motion n is equal to $\sqrt{(\mu/a^3)}$. For a 300 km (162 n.mi.) orbit around the earth, the period is 90.5 min, $n = 0.001157$ rad/s, and the circular orbital velocity is 7.73 km/s... The time derivative of each of these equations yields the corresponding velocity equations:

$$V_x = V_{x0}\cos(nt) + (2V_{y0} + 3nX_0)\sin(nt)$$

$$V_y = -2V_{x0}\sin(nt) + (4V_{y0} + 6nX_0)\cos(nt) - (3V_{y0} + 6nX_0)$$

$$V_z = -Z_0 n \sin t(nt) + V_{z0}\cos(nt)$$

Because position equations as a function of time are available, analytical solutions for trajectory location can be plotted without incurring the integration errors that would arise were the velocity equations integrated. The velocity equations are only used to determine the vehicle's velocity at the moment of thrust. The Δv components, in three axes, are then added to these velocity components to yield the new velocity components that are then inputted back into the position equations as the new initial velocity components. EivaN operates under the assumptions of no-drag, uniform mass distribution of the gravitational body, and instantaneous burns.

Received Feb. 5, 1990; revision received April 12, 1990.

*Aerospace Engineer/Research Psychologist, Sterling Software. Student Member AIAA.

EivaN is being used by researchers both domestic and international. NASA's computer data base, COSMIC, has evaluated eivaN and is in charge of its distribution.[4–6] *NASA Tech Briefs* will feature a description of eivaN in a forthcoming issue.

EivaN Operation

The eivaN screen appears in Fig. 1. Typically, only the first two columns are visible, with the rest of the screen reserved for the output chart. The following are modified excerpts from the eivaN user's manual.[7]

> Initial conditions are inputted in "Up," "Forward," and "Left" coordinates, as defined by an observer in a local vertical-local horizontal (LVLH) configuration facing forward along the + V-bar. (To people familiar with orbital mechanics, Up corresponds to + X, Forward is represented by + Y, and Left is mapped to + Z.) These values are set relative to any convenient "stationary" origin, such as the center of mass of the space station, and appear in boxes B2:B4. (See Fig 2.) The units are meters. In proposed space station reference axes, these directions correspond to -Z, + X, and -Y. To prevent confusion among the various conflicting and noncompatible coordinate systems, which include, but are not limited to, Greenwich True of Date, Geodetic, Space Station Reference, Orbiter Body Axis, Orbiter Structural Body, and Orbital Element,[8] the Up, Forward, Left system is used for input.
>
> EivaN plots twenty-one points for each thrust with a user-definable time interval that is entered in B5 in minutes. Fractional minutes are allowed for increased resolution. The first point appears at the instant of burn and twenty successive marks appear after the designated interval regardless of whether subsequent burns are made. Since twenty points resulting from burn 1 are plotted regardless of when and if there is a burn 2, the effect of each inputted thrust can be readily assessed and compared with the single burn condition. The type [color] of mark for each burn is distinct to facilitate this interpretation....
>
> ...One interesting visualization technique involves specifying the time of a burn but omitting the magnitude parameters. In this way, twenty-one data points for a trajectory can be drawn anywhere in time without altering the path. This method may be used to plot points after the time span of an orbital period, for example, or to continue the plot of a burn after twenty-one points. Input values for successive burns are installed in the same manner further down column B. Note: it is important to keep burns in chronological order, as the calculations may get disturbed otherwise.
>
> The rest of the worksheet contains the values for the data points, as well as all intermediate data. Actual position locations can be read from the spreadsheet in addition to the velocity components just prior to each burn. A knowledge of [the software application] is helpful for advanced interpretation of the worksheet....

Figure 3 illustrates the out-of-plane component of orbital motion. This motion is described as simple harmonic motion and is uncoupled from movement in the other two axes. In other words, thrusting to the left does not produce motion upward or forward.

Although the axes in eivaN's output chart are automatically scaled to accommodate all of the data points, the minimum and maximum values for each axis can be altered by the operator to focus on any particular area of interest. For example, the graph can be fixed to plot only the activity occurring within a 100 m cube centered at the origin, or an area 200 m long and 50 m high located 75 m behind the origin. The charts can also be customized with the addition of text and arrows.

The eivaN package includes a macro that precludes the necessity of searching the eivaN spreadsheet for individual range and rate components. After the macro receives the burn number and time information describing a specific point, it calculates and displays the three-axis range and rate information. The macro

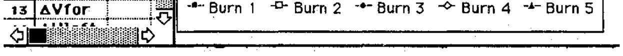

Fig. 1 Combined eviaN input/output window showing trajectories resulting from two burns.

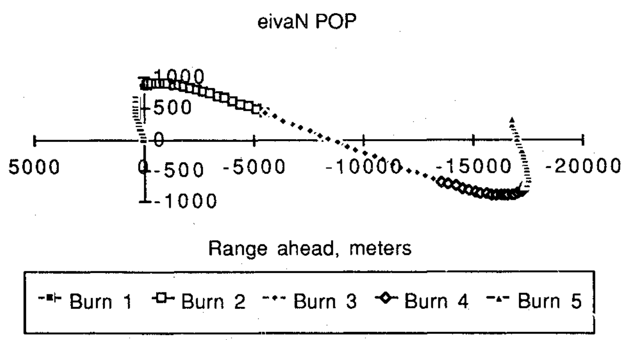

Fig. 3 EviaN POP showing result of 1 m/s burn left and 1 m/s forward.

	A	B	C	D	E	F	G	H
1	IC	1				*Burn 2 coordinates*		
2	up	0				1373	-91.8	0
3	forward					*nt*	1.328	
4	left					*sin(nt)*	0.971	
5	interval	1				*cos(nt)*	0.24	
6	Burn 1		*6nxo*	0		*6nxo*	9.117	
7	ΔVup		*Vx0/n*	0		*Vx0/n*	1754	
8	ΔVfor	1	*Vyo/n*	904		*Vyo/n*	-1842	
9	ΔVleft		*Vzo/n*	0		*Vzo/n*	0	
10						Pre-burn 2 velocity		
11	Burn 2					1.941	-2.04	0
12	ΔVup							
13	ΔVfor			Position 1			Position 2	
14	ΔVleft		0	0	0	1373	-91.8	0
15	time, s	1200	3.983	60	0	1490	-222	0

Fig. 2 EviaN input spreadsheet.

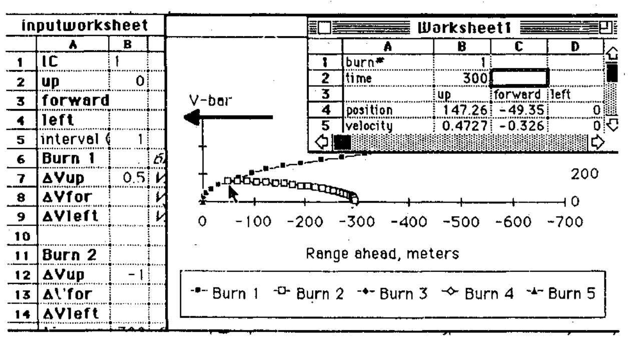

Fig. 4 EviaN macro showing range and rate data for point at 300 s on burn 1.

can be run a multiple number of times to simultaneously present the state information for a multiple number of locations and each will be updated appropriately with each change in the data on the spreadsheet. Each open spreadsheet will cumulatively increase the computation time; however, any or all of them may be closed at any time (see Fig. 4).

EivaN Utilization

EivaN has been used successfully in several different studies. The first evaluated its usefulness to naive subjects in planning a series of eight different space station docking maneuvers.[9] In the second study, eivaN was used to determine velocity increment Δv values for the self-rescue of a stranded extra-vehicular activity (EVA) crewperson.[10] Researchers around the country and internationally are using eivaN for other studies.

Experiment One

In the first study, eviaN was one of two interactive displays used by subjects to plan docking maneuvers to the space station. Docking maneuvers to a space station in a 300-km orbit were planned from eight starting positions at a range of 300 m. These points were situated at 45 deg intervals in the orbital plane. Subjects were instructed to have the trajectory intersect the center of mass of the space station and were limited to two burns between 0.1 and 9.9 m/s inclusive in magnitude.

Results indicated how rapidly the use of eivaN can be learned by untrained individuals as all subjects demonstrated rapid learning. The data also showed that the starting location above and behind the station required the most fuel and that the mission from directly below the station required the most number of burns. These values relate to the planning of maneuvers and,because the orbital mechanics equations were included in the simulation, there should be a correspondence between planning and actual flight.

Experiment Two

EivaN was also used to estimate the velocity increment Δv required for an EVA crewperson to return to the station after accidental separation. The separation was modeled as a 2 m/s departure from 47 m above the center of mass of the station. The researchers inputted a series of burns in order to provide the simulated crewperson with the trajectory necessary to recontact the station. The velocity increments were then summed to arrive at the total translational velocity increment. Other individuals are currently using eivaN to further explore EVA rescue techniques.

New Improvements

The latest version of the software on which eivaN runs includes a macro that is very useful with eivaN. *Goal Seeker* determines the appropriate value of an independent variable given a target value for a dependent variable. In other words, eivaN can compute the value of an independent variable necessary to achieve a user-targeted value for a dependent variable. For example, with initial and final positions and Δv components specified, eivaN will calculate the time (if a solution exists) to get from start to finish given the specified velocity increment values. Alternately, if a solution is available, eivaN can compute the appropriate "ΔvUp" to get from one location to another, given the time and "ΔvForward."

Also, through an inverse calculation, eivaN can produce the two velocity increment components necessary for a one-burn maneuver, given a specified mission duration. This algorithm is the one used by Navie, a backward-looking course plotting tool. The name eivaN was derived from Navie as well since eivaN provides a forward-looking solution in that burns are inputted and locations calculated rather than the opposite, as in Navie.[1]

References

[1]Grunwald, A. J., and Ellis, S. R., "Interactive Orbital Proximity Operations Planning System," NASA TP-2839, Nov. 1988.

[2]Kaplan, M. H., *Modern Spacecraft Dynamics & Control*, New York, 1976, p. 112.

[3]Brody, A. R., "Spacecraft Flight Simulation: A Human Factors Investigation into the Man-Machine Interface Between an Astronaut and a Spacecraft Performing Docking Maneuvers and Other Proximity Operations," S. M. Thesis, M.I.T., Cambridge, MA, April 1987; see also NASA CR-177502, Sept. 1988.

[4]COSMIC, "COSMIC Microcomputer Software 1990 Edition," Univ. of Georgia, Athens, GA, 1989.

[5]COSMIC, "Trajectories and Orbital Mechanics Collection A Selection of Computer Program Abstracts," Univ. of Georgia, Athens, GA, 1989.

[6]COSMIC, "Software Catalog 1990," NASA CR-185888, 1990.

[7]Brody, A. R., "EviaN: A Forward-Looking Interactive Orbital Trajectory Plotting Tool for Use with Proximity Operations (PROX OPS) and Other Maneuvers Description and User's Manual," NASA CR-177490, June 1988.

[8]Space Station Program Office, "Space Station Reference Coordinate Systems," Johnson Space Center, Houston, TX, JSC-30219, 1986.

[9]Brody, A. R., Ellis, S. R., Grunwald, A., and Haines, R. F., "An Evaluation of Interactive Displays for Trajectory Planning and Proximity Operations," Digital Avionics Systems Conf., San Jose, CA, Vol. 2, Oct. 1988, pp. 542–547.

[10]Brody, A. and Lomax, C., "Development of an Extravehicular Activity Self Rescue Technique for Space Station," Society of Automotive Engineers, Warrendale, PA, SAE 891594, July 1989.

James A. Martin
Associate Editor