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Automated Maneuver Planning Using a Fuzzy Logic Algorithm*

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Abstract

Spacecraft orbital control requires intensive interaction between the analyst and the system used to model the spacecraft trajectory. For orbits with tight mission constraints and a large number of maneuvers, this interaction is difficult or expensive to accomplish in a timely manner. Some automation of maneuver planning can reduce these difficulties for maneuver-intensive missions. One approach to this automation is to use fuzzy logic in the control mechanism. Such a prototype system currently under development is discussed.

The Tropical Rainfall Measurement Mission (TRMM) is one of several missions that could benefit from automated maneuver planning. TRMM is scheduled for launch in August 1997. The spacecraft is to be maintained in a 350-km circular orbit throughout the 3-year lifetime of the mission, with very small variations in this orbit allowed. Since solar maximum will occur as early as 1999, the solar activity during the TRMM mission will be increasing. The increasing solar activity will result in orbital maneuvers being performed as often as every other day. The results of automated maneuver planning for the TRMM mission will be presented to demonstrate the prototype of the fuzzy logic tool.

Introduction

Near-Earth missions flown during periods of high solar activity perform frequent maneuvers to overcome atmospheric drag. Missions mapping the Earth perform frequent maneuvers to maintain a precise groundtrack. Missions involving multiple spacecraft maneuver frequently to maintain the spacecraft formation over long periods of time. All of these missions contain a common control problem: for the spacecraft to maintain a precise orbit, frequent maneuvers must be planned and executed.

Maneuver plans are created well in advance of the maneuvers to facilitate fabrication of spacecraft commands and communications scheduling. As the time between maneuvers shrinks, the frequency of the planning function increases, and total costs rise. Automating maneuver planning can reduce these costs. If the constraints applied to a mission are simple and do not conflict, the control process is straightforward and can be implemented using simple checks on orbital parameters. As the complexity of the problem rises, this technique becomes intractable, and conflicting constraints become difficult to resolve. For such cases, bivalent logic employed for maneuver planning behaves poorly because the domain of the solution space shrinks quickly.[1] Multivalent logic systems overcome this difficulty by triggering appropriate actions as specified combinations of conditions are met.

An example of a mission that can benefit from maneuver automation is the Tropical Rainfall Measurement Mission (TRMM). TRMM is scheduled for launch in August 1997. The spacecraft must remain at a mean geodetic altitude of 350 km throughout its 3-year lifetime. Only very small variations in this orbit are allowed.

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Since a solar maximum will occur as early as 1999, increasing solar activity during the TRMM mission will require frequent maneuvers. Figure 1 shows the evolution of the maneuver timing for the TRMM mission. Maneuvers will be performed nearly every other day during periods of high solar activity. Since station contacts and data collection must be planned 5 weeks ahead, TRMM is an ideal mission to test multivalent logic systems for automated maneuver planning.

Multivalent Logic Systems

Bivalent logic was introduced by the Greek philosopher Aristotle. Any statement in Aristotelian logic is either true or false. A system composed of such statements is simple to manipulate. Problems arise in Aristotelian logic systems when certain types of statements are combined: the resulting conclusions can be contradictory. The most common example where neither case can be true is the speaker who states "I am lying." If the speaker is lying, then the statement must be a lie. But if the statement is a lie, then the speaker must be telling the truth. Mathematical deduction can produce similar contradictions. Mathematicians began examining techniques for resolving this type of inconsistency in set theory in the early 1900s.[2] One of the resulting branches of mathematics is propositional calculus. It provides the basis for logic systems that allow for more flexibility than is available with bivalent (true/false) logic systems. An example of such a multivalent logic system is fuzzy set theory, often referred to as fuzzy logic.

Fuzzy logic was introduced in 1965 as a generalization of conventional set theory.[3] It provides a mathematical structure for representing indeterminate results. In this paper, fuzzy logic is examined as a technique to automate maneuver planning for spacecraft missions. We begin by outlining fuzzy set theory and its application to control problems and discuss using fuzzy logic to automate frequent maneuvers. The maneuver constraints that fuzzy logic satisfies for TRMM are examined, and fuzzy logic is used to plan a sequence of maneuvers for the TRMM mission during a period of high solar activity. After examining this application, the strengths of fuzzy logic for maneuver planning are discussed, and some concluding remarks are offered.

The mathematics behind fuzzy logic are well founded. They provide crisp, reproducible results for a given application of the theory. The terminology used to describe fuzzy logic can be confusing.[4] The basic building blocks of the theory are "fuzzy sets." The domain of each set is defined by a parameter in the real world. The "fuzziness" of the theory arises when evaluating values of the parameter. Any parameter value used in classical set theory would be either in the set or out of it. In fuzzy set theory, the set is defined such that parameter values may be partial members of a set. The "degree of membership," a number between 0 and 1, that the value takes determines the way that it is used in the fuzzy logic system. The process used to convert a measured value into a fuzzy set is called "fuzzification." This process takes the measured value and converts it into a fuzzy set. Once all of the fuzzification has been performed, a set of rules is applied to evaluate the consequences of the measured values, producing a fuzzy set. That set is converted into a number used in the real world through a process called "defuzzification." The details of this procedure are described below.

Fuzzification/Evaluation/Defuzzification:

The TRMM altitude constraint is not precise. It can be expressed in terms like "the mean geodetic altitude must be maintained at 350 ± 1.25 km," but the altitude specified is an averaged (mean) parameter and limits the amount of precision available for control. Fuzzy set theory evaluates such nebulous constraints by assigning a membership to each value in the domain of the problem. For example, the TRMM altitude constraint can be represented by the set shown in Figure 2. In this figure, each geodetic height is assigned a unique degree of membership in the set of "acceptable" altitudes. A geodetic height of 349.0 km with a membership 0.9 is more a member of this set than not a member. Similar statements can be made about any height value. Some geodetic heights belong completely in the acceptable altitude set and have a membership of 1.0; others belong only partially to this set and have a membership value between 0.0 and 1.0; still others do not belong at all—their membership value is 0.0.

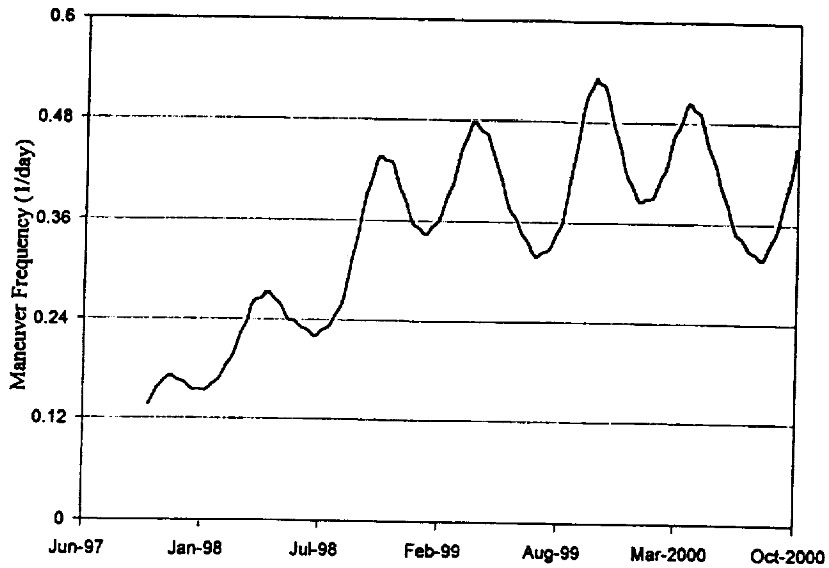

Figure 1. TRMM Maneuver Frequency

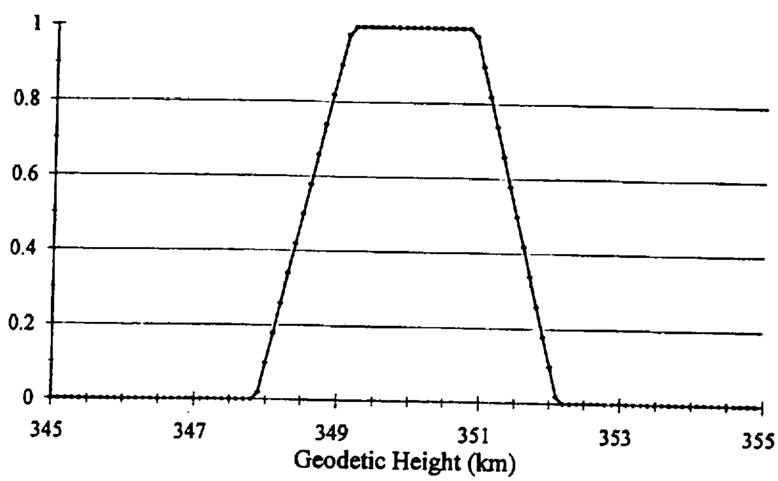

Figure 2. The Geodetic Height Set, *H*

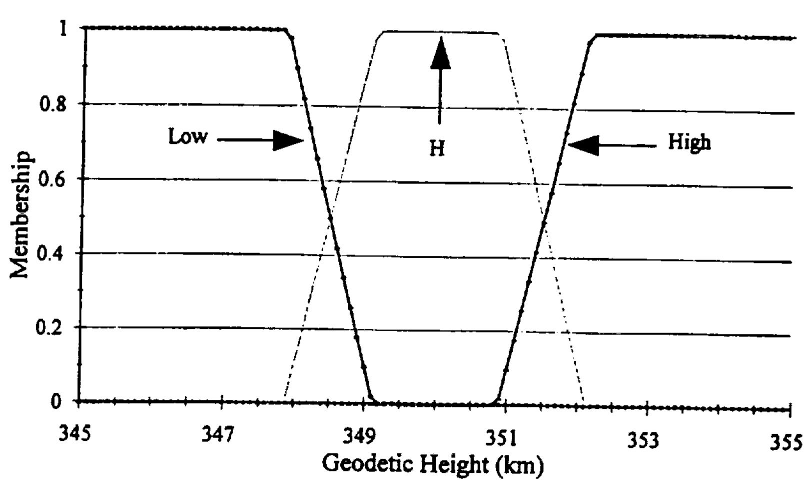

Figure 3. The *High* and *Low* Sets

Sets like the one described are the building blocks of fuzzy set theory. Once the appropriate sets have been constructed for a problem, they are manipulated to produce the desired results. To see how the sets produce the desired results, consider the action taken as the geodetic height decays for TRMM. If the geodetic height is low, a sequence of two maneuvers is performed to increase the apogee height and to circularize the orbit. Two sets describing low and high geodetic height are shown in Figure 3. The spacecraft is maneuvered according to the following rules:

- If the height is low and the apogee height is *not high*, then perform an apogee-raising maneuver.
- If the height is high and the perigee height is *low*, then perform a perigee-raising maneuver.
- If the height is acceptable (that is, in the acceptable geodetic height set—labeled H in the figures), then do nothing.

Each rule requires that three steps be taken.[5] First, each parameter (height, perigee height, or apogee height in this case) is used to transform the appropriate fuzzy set or sets. This is the "fuzzification" step. Second, the resulting fuzzy sets are combined into a single entity for evaluation. This entity is the resultant, fuzzy set R. Finally, the set R is evaluated to determine what actions should be performed. The last step is "defuzzification."

We will use a satellite at a geodetic height of 348.7 km and an apogee height of 351.8 km to illustrate this process at a specific point in time. The fuzzification that we use is accomplished by determining to what degree the physical parameters are a member of each fuzzy set. These memberships are used to construct a new set that has membership values less than or equal to the membership values of the corresponding physical parameters. In this way, the physical parameters are converted into fuzzy sets. For our example, evaluation of the first phrase listed after the *if* in the first rule, *the height is low*, proceeds as follows. The membership of the height h = 348.7 km in the fuzzy set *low* is 0.34. This degree of membership is used to limit the *low* set to a maximum membership value of 0.34, producing the new fuzzy set shown in Figure 4. It is identical to the *low* set, except that the degree of membership has been restricted as discussed here. Similar fuzzification is applied to each antecedent clause in every *if/then* rule.

Points addressed below include evaluating clauses like *not high*. The ability of fuzzy logic to encompass such seemingly ambiguous clauses enhances their adaptability to diverse problems. The *not high* fuzzy set has the appearance one would expect: membership $\mu_{\text{not high}}(h)$ is given by

$$\mu_{\text{not high}}(h) = 1.0 - \mu_{\text{high}}(h) \tag{1}$$

After all antecedent clauses of a rule have been evaluated, the resulting sets are combined to form a fuzzy set for defuzzification. This set is formed from the intersection of all of the sets produced from fuzzification. For example, the final set for the first rule is constructed by taking the intersection of the sets described by *the height is low* and *the apogee height is not high*. Such a construction is illustrated in Figure 5 for a geodetic height of 348.7 km and an apogee height of 351.8 km. The final fuzzy set is shaded for clarity.

"Defuzzification" is performed by evaluating the location in the set of a single value representing the contents of the set.[6] This evaluation can involve one of several methods. The simplest method is to find the point at which membership in the set has its maximum value. If more than one such point exists, as for the set in Figure 5, the center of the maximal region is taken as the representative value. For the set displayed in the figure, this maximum method yields a height value of 346.900 km. The representative value can also be determined from the centroid of the set. The centroid is defined as

$$R_{\text{centroid}} = \frac{\int r\,d\mu}{\int d\mu} \approx \frac{\sum r_i \mu(r_i)}{\sum \mu(r_i)} \tag{2}$$

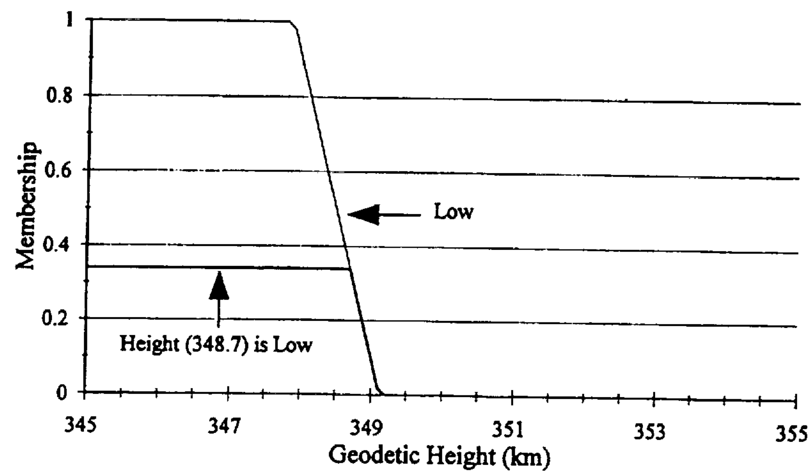

Figure 4. Fuzzification of *H* = 348.7

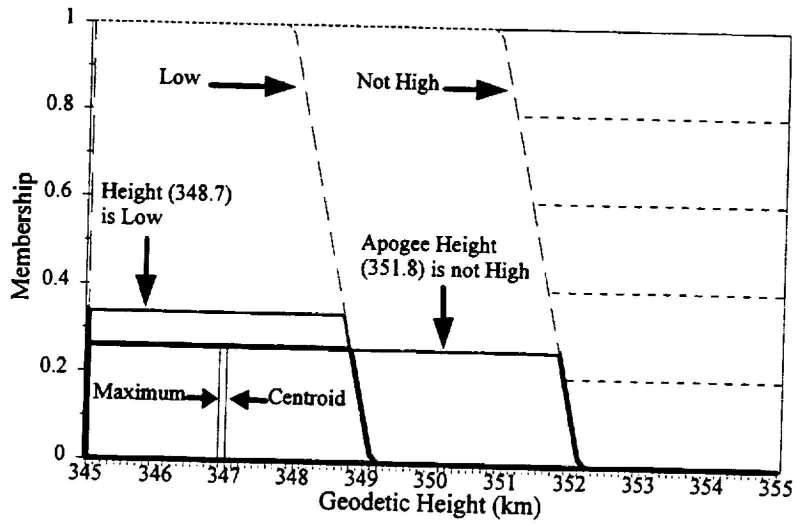

Figure 5. Fuzzified *If* Clause

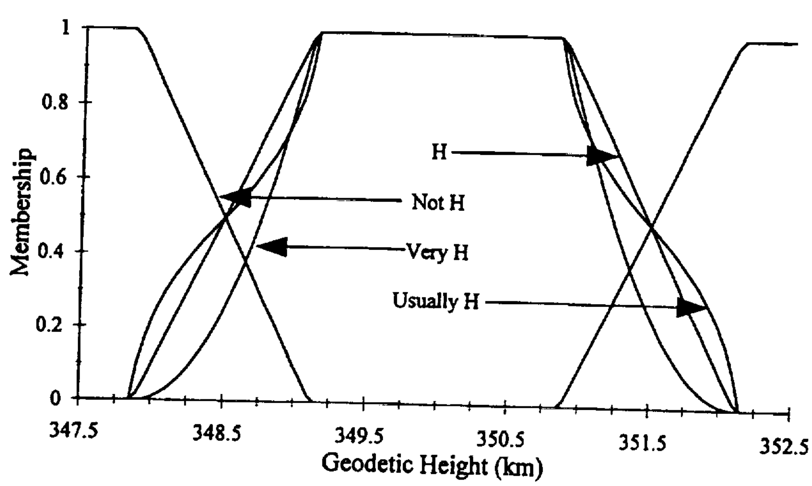

Figure 6. *H* and Some Hedges

The centroid of the set displayed in Figure 5 is at a height of 346.959 km. This point is labeled on the figure. Once the representative value has been determined, the degree of membership for that value is calculated and compared with a user-specified "threshold" value. The threshold value is chosen as the degree of membership required to trigger the consequence of the rule. If the membership is greater than or equal to the threshold value, the consequence of the rule is executed. For the set in Figure 5, the membership value both at the centroid and at the maximum is 0.26. If the firing threshold is set to 0.25, the consequence of the first rule (an apogee-raising maneuver) is executed; otherwise, it is not.

The procedure outlined above exemplifies the behavior of our fuzzy logic engine. Other methods of evaluation and defuzzification can be implemented for various types of problems. The method outlined here was chosen because it is simple and directly applicable to spacecraft control. The largest drawback to this approach is that it has no provision for a consequent action that contains variable parameters—for example, the spacecraft engines considered here are either on or off with no throttling. Variable throttling can be controlled with a fuzzy logic system.[7]

Although the fuzzy sets described above are simple, they are sufficient for spacecraft stationkeeping and orbit maintenance. Rather than design complicated fuzzy sets, we use simple sets that can be shaped to match our problems in a natural manner with linguistic hedges. The next section describes the techniques used to shape the sets.

Set Shaping and Hedges:

The fuzzy sets described above are coarse fits to the parameters that control a spacecraft maneuver. Precise control of a spacecraft with fuzzy logic requires that the sets be shaped to emphasize the parameters that control the spacecraft trajectory. Such shaping uses linguistic hedges.[8]

The set displayed in Figure 2 that describes acceptable geodetic height was constructed by piecing together five straight line segments between a height of 345 and 355 km with membership values between 0 and 1. These line segments may not be sufficient for the control problem. They form a rough picture of the region that defines the acceptable mean geodetic height for TRMM.

The control laws are composed of terms like *if the height is very low, then maneuver*. The word *very* modifies the meaning of *low*. It is a linguistic hedge applied to the set that describes low height. Such a hedge is implemented by taking the degree of membership at each value of the height, point by point, and squaring it. The degree of membership of the *very low* set is given by

$$\mu_{\text{very low}}(r) = \left[\mu_{\text{low}}(r)\right]^2 \tag{3}$$

This definition decreases the degree of membership of every point with partial membership in the set *low*. A point with membership 0.5 decreases to 0.25. Shaping matches the mathematical construction of the *very low* set to the linguistic meaning of *very low*. Direct mapping from natural language to a mathematical implementation is a key feature of fuzzy logic systems.

Three other types of hedges implemented in our maneuver planning tool, as well as the two hedges defined above, are listed in Table 1. The effects of these hedges are illustrated in Figures 6 and 7. Each hedge shapes the basic fuzzy set (*H* in the figure) to represent the meaning of the word attached to the hedge. The *not* hedge produces the inverse of the set. The *very* hedge sharpens the border of the sets by decreasing the membership of points with partial membership. The *somewhat* hedge broadens the border of the set by increasing the membership of points with partial membership. The *almost* hedge increases the membership of points with membership greater than 0.5 and decreases the membership of all other partial memberships. The *usually* hedge performs the inverse: points with nonzero membership less than 0.5 increase in membership, and those with partial membership greater than 0.5 decrease in membership. By implementing set shaping in this manner, the fuzzy logic system provides a direct mapping from the linguistic description of the problem to the mathematics of the sets. This direct mapping makes the system easy to understand and use.

Table 1. Some Basic Hedges

Hedge	Formula	
Not	$\mu_{not}(r) = 1.0 - \mu(r)$	(1)
Very	$\mu_{very}(r) = [\mu(r)]^2$	(3)
Somewhat	$\mu_{somewhat}(r) = \sqrt{\mu(r)}$	(4)
Almost	$\mu_{almost}(r) = \begin{cases} 2 \cdot [\mu(r)]^2 & \text{for } \mu(r) \le 0.5 \\ 1.0 - 2 \cdot [1.0 - \mu(r)]^2 & \text{for } \mu(r) > 0.5 \end{cases}$	(5)
Usually	$\mu_{usually}(r) = \begin{cases} \sqrt{\mu(r)/2} & \text{for } \mu(r) \le 0.5 \\ 1.0 - \sqrt{[1.0 - \mu(r)]/2} & \text{for } \mu(r) > 0.5 \end{cases}$	(6)

The Automated Maneuver Planning Tool

The purpose of maneuver automation is to calculate the timing and magnitude of spacecraft maneuvers from a set of general language rules determined by mission analysis personnel. The tool must calculate all necessary forces, integrate the spacecraft's equations, calculate relevant spacecraft events (orbital elements, shadow entry and exit, distances to appropriate bodies, and other geometric quantities), evaluate the maneuver rules with the fuzzy logic engine described above, compute thruster parameters, and include a user interface that provides access to data and parameters.

The force model implemented for the prototype automated maneuver tool contains a reduced representation of forces. The Sun, Earth, and Moon are treated as point masses. Oblateness of the Earth is included by using the J_2 through J_5 terms of the zonal expansion of the gravitational potential. Atmospheric drag is calculated from the Harris-Priester analytic drag model.[9] The evolution of the spacecraft's orbit is calculated with a ninth-order Runge-Kutta numerical integration scheme with an adaptive stepsize control derived by Verner.[10]

The fuzzy logic engine in the prototype tool works as described above. The user describes the sets as ASCII data and saves them to disk. The tool reads these sets and shapes them with the hedges described above. Each set has one or more events associated with it. Each event is fuzzified using the technique described above. Once every event in a given rule is fuzzified, the range of each set is scaled to fit the closed interval [0, 1]. This step simplifies processing the rules. The intersection of the sets is found, and defuzzification proceeds as described above. The firing threshold is usually set to 0.30. When defuzzification detects that a maneuver should be performed, an impulsive maneuver is executed. These maneuvers are calculated by interpolation of the appropriate delta-V data.

Applications to TRMM

The principal constraint on the TRMM orbit is specified in terms of the spacecraft's geodetic altitude: the spacecraft must maintain a mean geodetic altitude of 350 km, with variations of no more than 1.25 km. Since the orbit is inclined 35 degrees to the equatorial plane, the oblateness of the Earth results in geodetic height variations of about 7 km for a circular orbit. The calculation of orbital elements for use in the control system is further complicated by the effects of perturbations in the gravitational potential of the Earth which arise from oblateness and non-uniform mass distribution. When the oblateness of the Earth and its non-uniform mass distribution are included, the osculating orbital elements vary by as much as 6 km around each orbit. The oblateness of the Earth and non-uniform gravitational field cause the geodetic height of the spacecraft to vary 7.5 km about an altitude of 350 km.

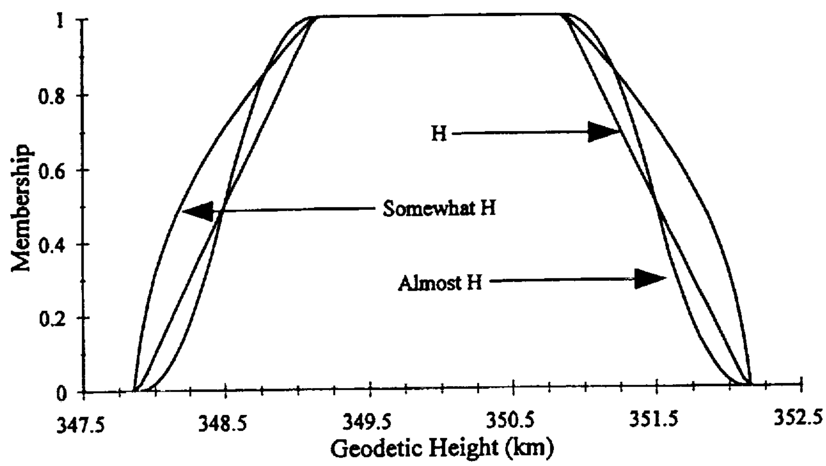

Figure 7. ***H*** **and Some Hedges**

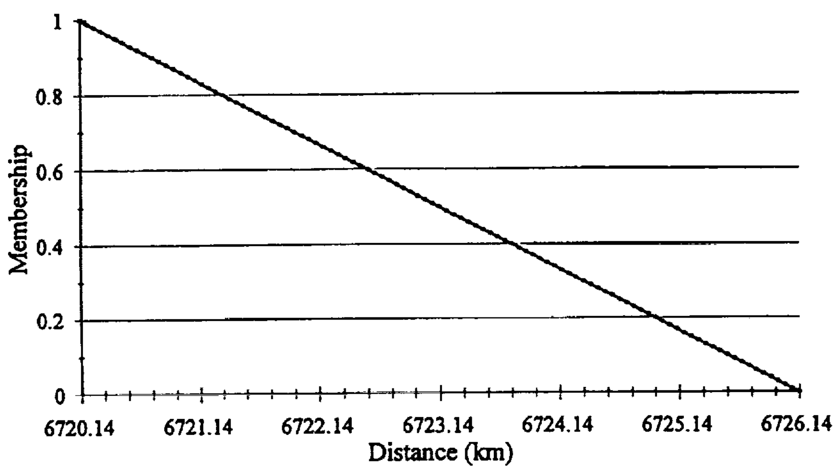

Figure 8. The *Low* Set

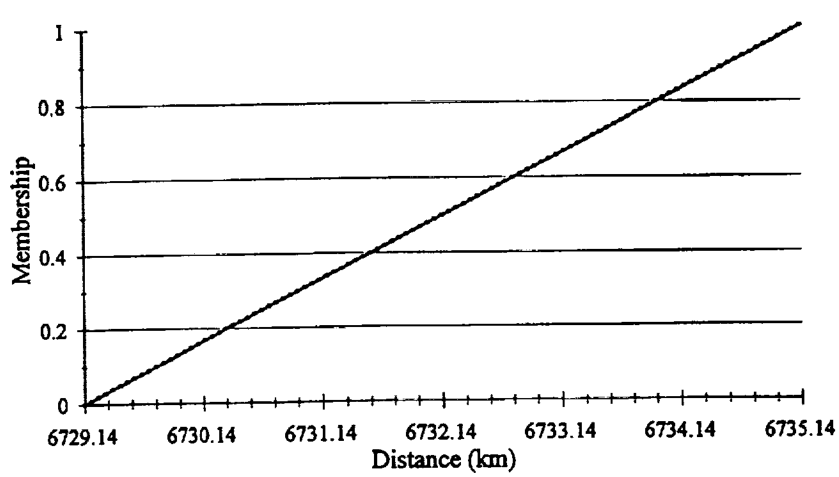

Figure 9. The *High* Set

We demonstrate below that automated maneuver planning can calculate the timing and magnitude of the maneuvers needed to maintain the TRMM mission orbit. We begin by describing the maneuver strategy and designing the appropriate sets required to implement this strategy for a force model that models gravitational effects as point mass effects only. This simplified force model will then be extended to include the effects of the zonal terms J_2–J_5 in order to demonstrate the refinements that must be made to the control sets to account for the more complicated physics of the extended force model.

A typical TRMM orbital state is given in Table 2. For this analysis, we treat it as the initial state of the spacecraft. The spacecraft mass varies from 3500 kg fully fueled to 2893 kg upon reentry. Since we are interested in the maneuver sequence near the end of the mission, we use a mass of 3000 kg as the initial spacecraft mass. The nominal surface area of the spacecraft is 15 m^2. The table of coefficients for the analytic Harris-Priester atmospheric model used here represents moderate solar activity. The effects of high solar activity are mimicked by increasing the coefficient of drag.

Table 2. A Sample TRMM Spacecraft State

UTC Epoch: 10/01/1999 00:00:00.000	
Earth-Centered Mean of J2000.0 Earth Equator and Equinox Osculating Keplerian Elements	
Semimajor Axis, *a*	6724.524 km
Eccentricity, *e*	0.000228
Inclination, *i*	35 degrees
Right Ascension of Ascending Node, Ω	0 degrees
Argument of Perigee, ω	90 degrees
True Anomaly, *TA*	0 degrees

The maneuvers demonstrated here require fuzzy sets that describe low and high distances from the center of the Earth and other fuzzy sets that describe regions near perigee (true anomaly of 0 degrees) and regions near apogee (true anomaly near 180 degrees). The four fuzzy sets representing the control parameters of the problem are shown in Figures 8–11. Note that all of the sets are simple. The *high* and *low* sets were formed by assigning a membership of 1.0 to those points defining the TRMM altitude box. The boundary of the box was spread over a 6-km region. The geodetic heights were added to the mean orbital radius of the Earth (6378.14 km) to produce the endpoints for a straight line defining the set. The *low* set was defined based on a minimum height of 342 km, so that the distance 6720.14 km (6378.14 + 342.00) from the center of the Earth is the highest point with membership 1 in the set, and the point 6726.14 (6378.14 + 342.00 + 6.00) is the lowest point with membership 0. Similar reasoning was used to construct the *high* set. The *periapsis* and *apoapsis* sets were constructed by placing a sinusoidal function at true anomaly (TA) values of 0 and 180 degrees. The functions were shaped so that their full width at half maximum was 36 degrees. Only one cycle of the function was used to generate each set.

The TRMM orbit control problem is fairly simple: after the spacecraft orbit has decayed to a low altitude, it is boosted to a higher altitude through a pair of maneuvers that approximate a Hohmann transfer. This control is achieved through a pair of statements:

- If the perigee radius is *very very low* and the semimajor axis (*A*) is *low*, then perform a maneuver to raise the apogee height to the maximum height allowed.

- If the apogee distance is *somewhat high* and the semimajor axis is *somewhat low*, then perform a maneuver to raise the perigee height to the maximum height allowed and make the resulting orbit (approximately) circular.

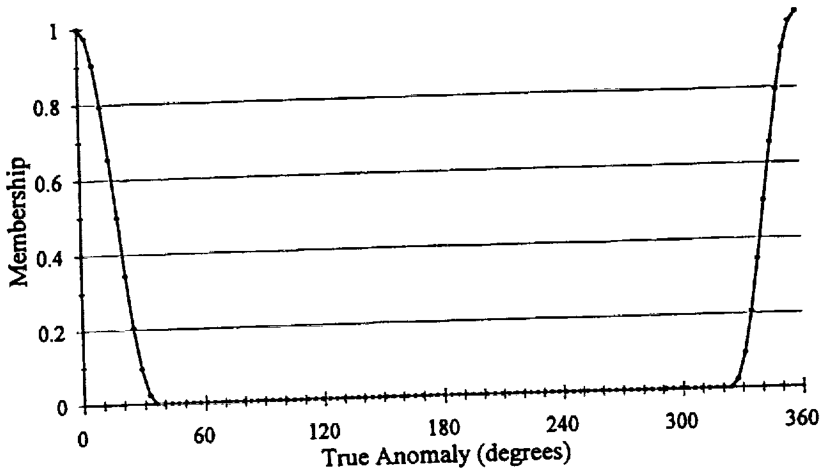

Figure 10. The *Perigee* Set

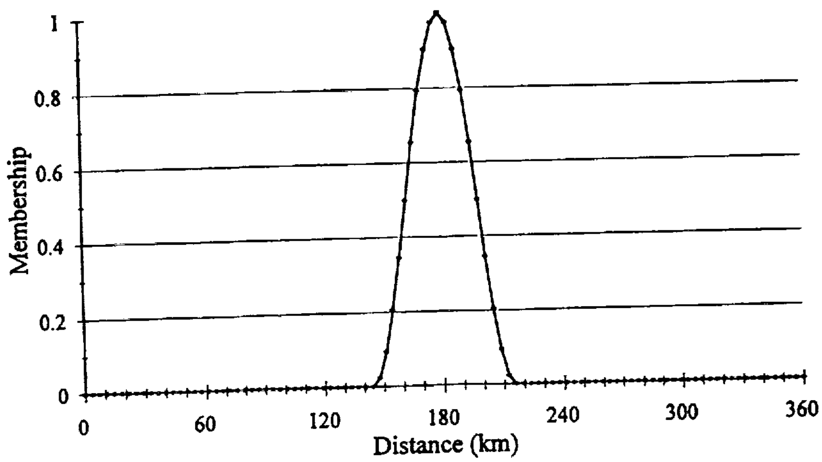

Figure 11. The *Apogee* Set

```
// This is a TRMM mission file propagating
// without the J2-J5 Zonal terms in the force model.
// Here is the command sequence...;

STATE = INITIAL_STATE;
//
// Propagate for two weeks;
WHILE EPOCH < 19991015.000000000;
        PROPAGATE;
        PLOT ELAPSED_DAYS APOGEE PERIGEE RADIUS A;
        PLOT ELAPSED_DAYS HEIGHT;

        IF PERIGEE IS VERY VERY LOW AND
          A IS VERY LOW AND
          TA IS PERIAPSE
        THEN VNB USING APOGEE FROM APOGEE.VNB;

        IF APOGEE IS SOMEWHAT SOMEWHAT HIGH AND
          A IS SOMEWHAT LOW AND
          TA IS APOAPSE
        THEN VNB USING PERIGEE FROM PERIGEE.VNB;

END;
FINAL_STATE = STATE;
```

Figure 12. Command Sequence for the TRMM Mission Without J_2 and Higher Terms in the Potential

The rules that perform this control are shown in Figure 12. Note the similarity of the statement of the orbit sequence (above) to the rules that control the fuzzy logic engine. Only the second rule differs. The statement description begins with the sequence *If the apogee distance is somewhat high. . . .* The corresponding rule begins IF APOGEE IS SOMEWHAT SOMEWHAT HIGH. . . . The second use of the hedge SOMEWHAT in the rule arose from experimentation designed to satisfy the mission constraints. If the second hedge is omitted, the second maneuver is not always performed, because the apogee height occasionally decays below the threshold value for the SOMEWHAT HIGH set before the spacecraft reaches apogee. This defect could be resolved by redefining the ***high*** fuzzy set. However, this would require regenerating the fuzzy set and retuning the logic engine. Instead, we used the SOMEWHAT hedge to shape the ***high*** set to match the observed apogee height data. This approach enabled us to experiment with and fine tune the control law without modifying the underlying algorithms or fuzzy sets, thereby demonstrating the simplicity and power of linguistic hedges.

The rules shown in Figure 12 are sufficient to drive the automated maneuver generation for the TRMM spacecraft. When these rules are applied to propagating the spacecraft from the initial state specification given above, under an Earth point mass gravitational force, maneuvers are performed as plotted in Figure 13. The geodetic height of the spacecraft is maintained between 344 and 359 km. The perigee height, semimajor axis, apogee height, and true anomaly of the spacecraft are computed at each propagation step. These parameters are fuzzified as described above and used to determine whether a maneuver is needed. When the defuzzification of the antecedent conditions specified in the *if/then* rule produce a value greater than the specified threshold, the consequent action is taken: in the TRMM case, a maneuver is performed to raise either apogee or perigee. For this analysis, the prototype interpolates the magnitude of the maneuver from a file of previously computed values and applies it impulsively to the spacecraft state.

The problem is more complicated when zonal terms of the Earth's gravitational field are included. The Keplerian orbital elements that act as control parameters oscillate with a magnitude comparable to the size of the box that defines the acceptable spacecraft orbits. Through experimentation, we found that the rules for orbit propagation using point masses can be modified to account for the effects of the zonal terms. These rules are shown in Figure 14. When these rules are executed using the TRMM initial state in Table 2, maneuvers are computed as displayed in the two graphs of Figure 15. The effects of atmospheric drag were exaggerated so that the behavior of the orbital elements could be seen. It was found that the osculating semimajor axis is not a good control parameter for the fuzzy sets defined in this section because at apogee it remains above the highest point in the *low* fuzzy set and never triggers consequences based on *low* semimajor axis values. Instead of using the semimajor axis value to control maneuvers, we use both the apogee and perigee distances to determine when the second maneuver of the Hohmann transfer should be performed. This method of control produces a sequence of maneuvers that maintains the TRMM orbit.

Because the maneuvers needed for TRMM are all nearly identical in nature, the maneuver strategy can be specified as a single set of conditions and consequences. Since the strategy is the same throughout the mission, a fuzzy logic controller can implement it repeatedly to automate maneuver planning tasks.

Strengths of Fuzzy Logic

Fuzzy logic controllers have several features that make them useful tools for maneuver planning automation. As is apparent from the preceding section, fuzzy logic control systems easily implement, in a simple manner, strategies for maneuvers that are nearly repetitive. Fuzzy logic does not require the conditions to be met identically each time for a maneuver to be generated. The fuzzy logic system evaluates the degree to which each constraint is met and triggers a maneuver based on this degree of membership.

A fuzzy logic control system can resolve conflicting constraints. Such a constraint would occur if TRMM maneuvers were to be performed only in sunlight. In such a case, the rules specifying that the first maneuver be performed at perigee must be relaxed. The periapsis and apoapsis fuzzy sets would be redefined to make them

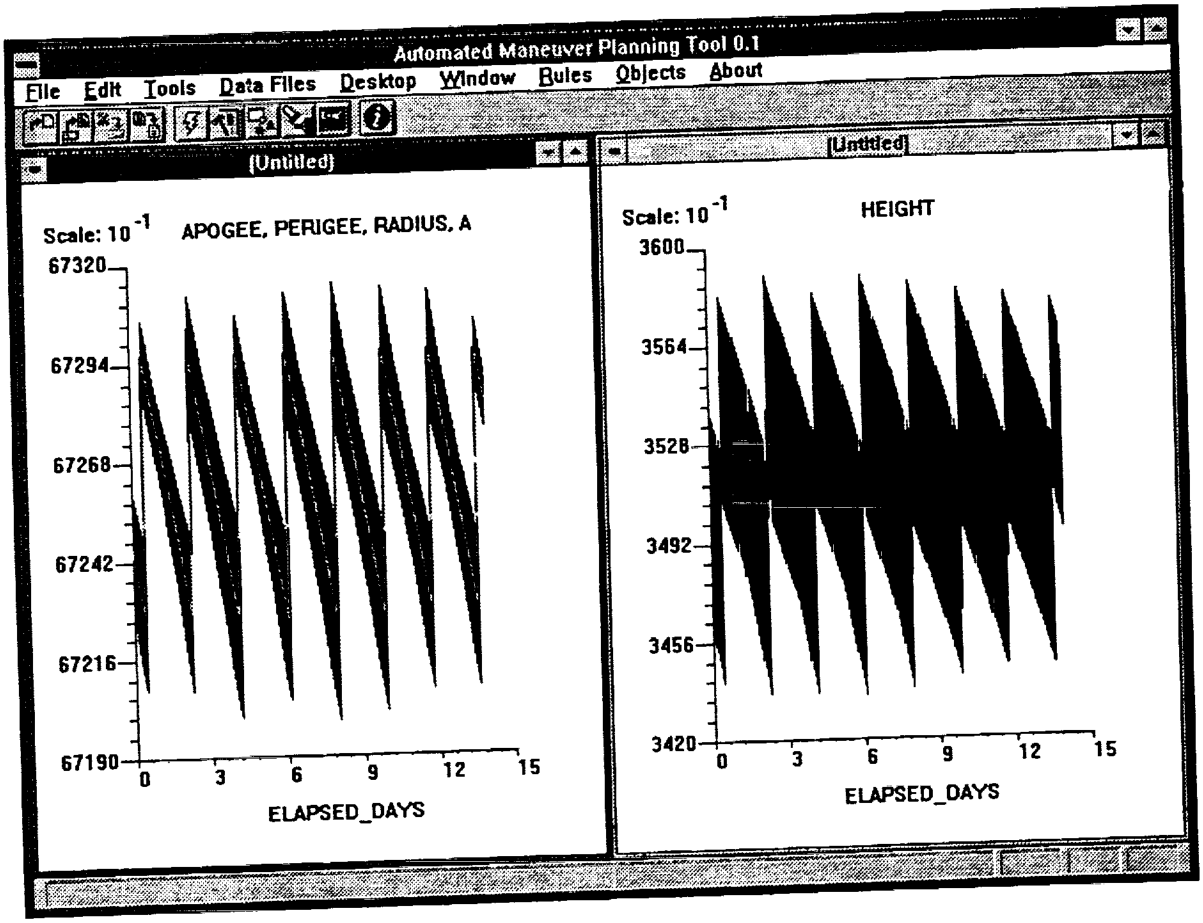

Figure 13. Two Weeks of the TRMM Mission (No Zonal Forces)

```
// This is a sample file for the automated maneuver planning tool. It is used to propagate the TRMM
// state;

STATE = INITIAL_STATE;

WHILE EPOCH < 19991005.000000000;
      PROPAGATE;

      PLOT ELAPSED_HOURS APOGEE PERIGEE RADIUS A;
      PLOT ELAPSED_HOURS HEIGHT;

      IF PERIGEE IS VERY LOW AND
        A IS LOW AND
        TA IS PERIAPSE
      THEN VNB USING A FROM APOGEE.VNB;

      IF APOGEE IS SOMEWHAT SOMEWHAT HIGH AND
         PERIGEE IS NOT VERY HIGH AND
         TA IS SOMEWHAT APOAPSE
      THEN VNB USING PERIGEE FROM PERIGEE.VNB;

      REPORT ELAPSED_HOURS HEIGHT RADIUS TO TRMM.DAT;

END;
FINAL_STATE = STATE;
```

Figure 14. The TRMM Mission Command Sequence for the Full Force Model

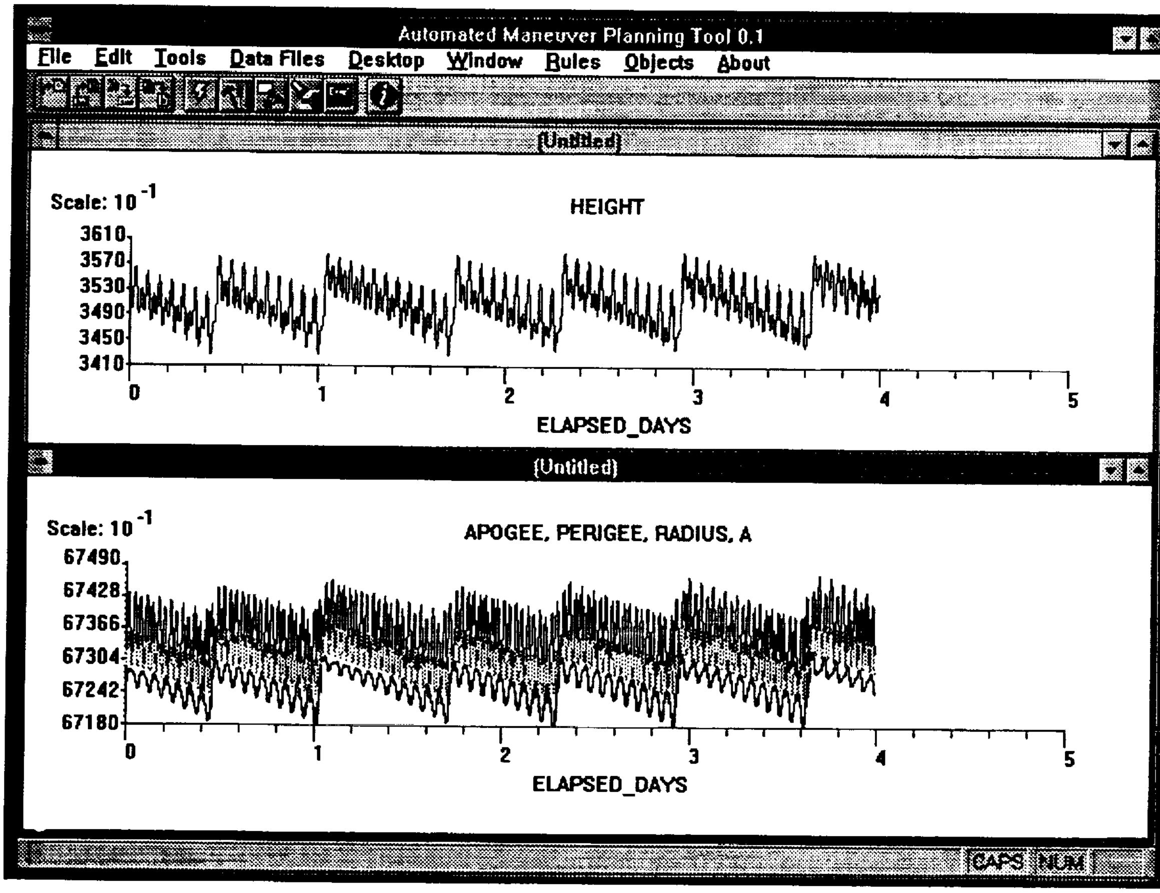

Figure 15. The TRMM Mission With Zonal Forces and Exaggerated Drag

broader than those shown in Figures 10 and 11. A new fuzzy set would be defined to match the Earth's shadow. Finally, the rules triggering the Hohmann transfer would be rewritten as follows:

IF PERIGEE IS VERY LOW AND A IS LOW AND TA IS PERIAPSE AND TA IS NOT SHADOW
AND TA IS NOT ANTISHADOW
THEN VNB USING A FROM APOGEE.VNB;

IF APOGEE IS SOMEWHAT SOMEWHAT HIGH AND PERIGEE IS NOT VERY HIGH AND TA IS
SOMEWHAT APOAPSE AND TA IS NOT SHADOW
THEN VNB USING PERIGEE FROM PERIGEE.VNB;

Note the use of the set ANTISHADOW. This set is used to keep the first maneuver in a region that allows the second maneuver of the Hohmann transfer (about 180 degrees away from the first) to be performed outside of shadow. This control strategy resolves the conflict between the shadow constraint and the Hohmann constraint on the location of the maneuvers. Similar techniques can be used to construct rules for other conflicting constraints.

Conclusions and Outlook

Fuzzy logic provides a linear mapping between maneuver planning and the way that maneuver strategies are specified. Linguistic variables and hedges make the control logic easy to define, use, and maintain. This ease of use encourages experimentation with the system and the development of innovative approaches to maneuver planning tasks. The resulting maneuver strategies are simple to interpret and tune to meet new mission constraints as mission plans evolve.

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