

THE CONCEPT OF PATH OBJECTS

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Background

There is the old joke about the novice at the annual “Joke Writers of America” conference. As each speaker gets up to speak, he introduces his talk with two numbers and the audience erupts into laughter. The young novice asks a person seated next to him to explain. The person says, “Because all the participants know all the jokes, each joke has been given a number. Also, the greatest joke writers of all time have been given identification numbers. So each speaker gives the joke’s number and the number of a famous writer who might have delivered it. We can each then know exactly what the delivery would have been. Some of the combinations are just hilarious.” We all know the punch line; “Some people just can’t tell a joke.”

The concept of Path Objects is similar in that it proposes placing processing capability in every Flight Management System (FMS) (or area navigation computer system) so that each can calculate a flight path from a minimal amount of information.

When the author was explaining this concept to a former controller, the controller said that he had used a similar concept in the early 70’s while controlling traffic going into Los Angeles. By prior agreement with the pilots of certain airlines, there was a convention for delivering instructions for a delay maneuver. If the controller said “delay left, one minute,” that meant that the aircraft was to turn left 30 degrees, fly one minute, turn right 60 degrees, fly two minutes, turn left 30 degrees and rejoin the route. It saved issuing and reading back two vectors per aircraft.

Path Objects

Path Objects are instructions stored in a computer such as the FMS (or any area navigation system) for constructing a flight path based on a few inputs in the form of fixes and parameters. For example, if we wanted to have the aircraft fly a circle, we would store (in the FMS) the instructions for how to construct the circle given just the center (a geographical fix) and the radius (a parameter). By sending the values of only those two arguments to the aircraft, we could locate the circle over the White House or the Kremlin by merely changing the center. We could change the radius by changing only one number. Furthermore, anyone could reconstruct the identical circle by just knowing the center and radius.

The use of Path Objects permits the controller (or automation system) and pilot (or FMS) to exchange intent information reliably, unambiguously, and efficiently, in a voice or datalink environment. In so doing, it helps provide a transition path to full automation while the world’s aircraft are partially equipped with data link. In a pure datalink environment, it reduces the amount of information that must be exchanged to maintain the integrity of intent information.

Characteristics of Path Objects

There are not that many types of path objects that would be required to define the types of maneuvers that are performed by commercial aircraft. Fundamentally, aircraft fly straight, turn a number of degrees, fly an arc of a certain radius, or fly a standardized pattern (such as a traffic pattern or procedure turn).

Consequently, with just a few shapes we can define all of the FMS routes in the world.

Path Object shapes are defined independently of their location. Consequently, an aircraft with Area Navigation (RNAV) capability such as with the Global Positioning System (GPS), need only carry these shapes with it to be able to fly any FMS route anywhere in the world. The control system can dynamically change FMS routes by changing parameters. This offers a tremendous increase in flexibility over pre-defined FMS routes that must be loaded into the FMS prior to take-off. Path Objects are based entirely on RNAV.

Types of Path Objects

Lines

Figure 1 shows a simple line segment.

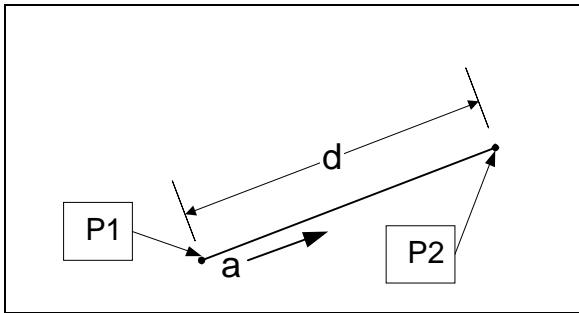


Figure 1: Line Path Object

If this path is called “L1”, then it only needs two points to implement it. For example, the simple notation, [L1, **P1**, **P2**], where **P1** = (x1,y1,z1) and **P2** = (x2,y2,z2) completely defines the path. The fixes, **P1**, and **P2**, are three dimensional fixes using latitude, longitude and barometric altitude. The Path Object in this case consists of the instructions (stored in the computer under the label ‘L1’), and the two parameters, **P1** and **P2**. The distance from **P1** to **P2** is calculated by the relationship,

$$d = \sqrt{|\mathbf{P1}|^2 + |\mathbf{P2}|^2 - 2 \times \mathbf{P1} \cdot \mathbf{P2}}$$

However, any algorithm or representation that produces an identical path is acceptable. The philosophy for developing Path Objects is that there should be alternative representations for the same path so that the ATC application can choose the one that is most convenient.

An alternative way to express this is in the form of a course, “a,” from **P1** for a distance d, with altitude change “c.” This would be stored as [L2,**P1**,a,d,c]. The instructions in the POP would be to fly from **P1** along course “a” for a distance “d,” and change altitude by an amount “c.” There is a functional relationship between L1 and L2, so that the same path can be expressed in either notation.

Turns

Similarly for a turn, there are several equivalent ways to express the turn. Figure 2 illustrates the basic turn.

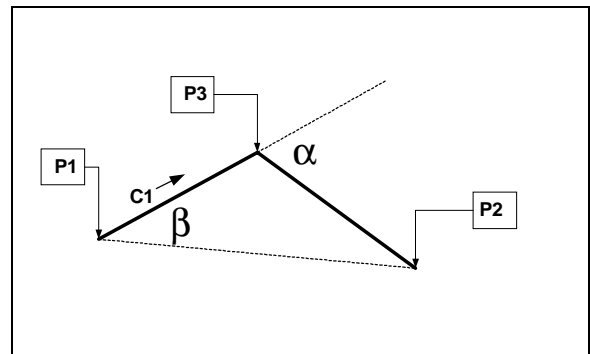


Figure 2: Basic Turn Path Object

Figure 2 illustrates two definitions of the turn. It is possible to simply specify the three points, **P1**, **P2**, and, **P3** as [T1, **P1**, **P2**, **P3**]. The instructions in the computer would then turn the aircraft at **P3** with a sufficient angle to fly directly to **P2**.

Another method would be to specify **P1**, the angle β , **P2**, and the angle, α , using the notation [T2, **P1**, **P2**, β , α].

The FMS would then fly from **P1** along the course C1 (calculated from the course **P1**-

P2 and β) until the relative angle between the aircraft and **P2** was α , at which point it would turn toward **P2**. The choice of definition T1 or T2 would depend on whether the user wanted additional altitude control at point **P3**.

Analogous to the course-distance representation of a line where the altitude is constant, a turn could be specified by providing a starting point, **P1**, an initial course α , for a distance $d1$, and a second course, β , for a distance $d2$, using the notation [T3,**P1**, α , $d1$, β , $d2$].

Arcs

In situations where the ATC system wanted tighter specification of the area where the aircraft turns, the turn Path Object could take on other parameters as shown in Figure 3. This turn Path Object is specified as [T4, **P1**, **P2**, **P3**].

The path begins at **P1**, then follows a path to **P3** where the path turns along a circle of radius 3 nmi, with center on the normal to **P1-P3** at **P3**. The center is on the same side of the line **P1-P3** as is **P2**. It then follows the path emanating from **P2** that is tangent to the circle.

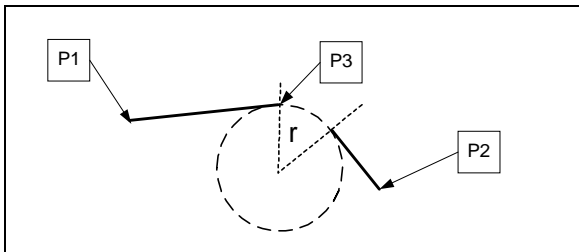


Figure 3. "Turn Radius" Path Object

The turn radius object could also be useful in a free flight setting when the aircraft wanted to convey to the ground that it was going to deviate around a thunderstorm.

Patterns

There are a number of patterns that aircraft use for purposes such as path extensions and positioning.

The most common is the holding pattern. In Figure 4 we have defined a holding pattern by two fixes and a course. This can be expressed as [H1,**P1**,**P2**, a].

The instructions for H1 calculate the rectangle having corners at **P1** and **P2** and fly two 180-deg course reversals at the ends. The pattern is oriented so that the aircraft is on course "a" as it approaches **P1**.

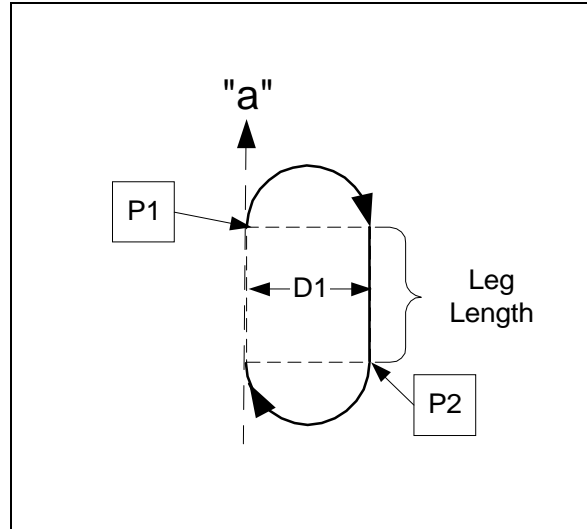


Figure 4. Holding Pattern Object

Many flight management systems already have a holding function. The pilot only has to specify the point **P1**, the course "a", and the length of the legs. This is done using a keypad entry method. The parameter **D1** is not specified and the assumption is that if the aircraft executes a standard rate turn at **P1**, it would stay within reasonable limits.

Another common pattern is the "traffic pattern" or "circuit." The aircraft typically follows a path parallel to the runway in the opposite direction of the approach path, goes beyond the runway for a certain distance, then executes a 180 degree turn and lines up with the runway centerline. This object is shown in Figure 5.

This Path Object is encoded as [TP1, **P1**, c , $d1$, $d2$, $d3$]. The flight path is constructed from **P1**, by having the course line, C , pass by **P1** at a distance, $d1$. From that, the

dimension d2 determines the starting point and the distance d3 determines the start of the turn to base and the length of the final approach.

The traffic pattern Path Object can be combined with a turn path object to form a basic Standard Arrival Route (STAR).

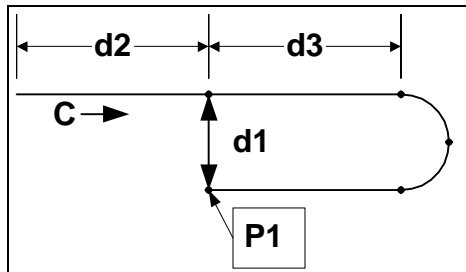


Figure 5. Traffic Pattern Path Object

The notion of a path stretching Path Object is shown in Figure 6. This is similar to the anecdote about the delay maneuver used in Los Angeles. The idea is that an aircraft traveling from **P1** along course “C” must insert a *S-turn* maneuver along the course that adds “N” nmi to the path within P nmi after **P1**.

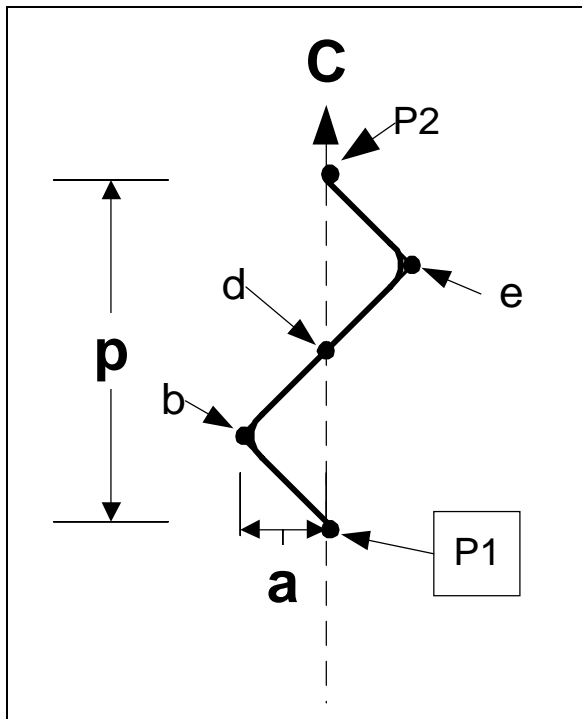


Figure 6. Path Stretching Maneuver "PS1"

The notation is [PS1, **P1**, C, N, p]. The instructions are then to calculate the path of an *S-turn* that adds N nmi to the path starting at **P1**. Such a path has an amplitude of “a” and a period of “p” along the course “C,” starting at P1. The legs P1-b, b-d, d-e and e-P2 are all required to be the same length. The length from P1 to b is

$$\sqrt{a^2 + \left(\frac{p^2}{16}\right)}$$

The length X of the path P1-b-d-e-P2 is 4 times that, or:

$$X = \sqrt{(4a)^2 + p^2} = p + N.$$

The amplitude of the deviations, “a,” would then be calculated from the relationship

$$\sqrt{(4a)^2 + p^2} = p + N.$$

$$a = \sqrt{\frac{(N^2 + 2Np)}{16}}$$

The controller could then issue a command such as “Extend your path by N nmi beginning at fix P1, within p nmi, along course C.” The controller can do this anytime before the aircraft reaches P1, leaving him free to concentrate on other activities. The pilot would simply pull up the “Path Stretch” page, insert the parameters and the FMS would execute the maneuver.

Other path object patterns are being developed and have been published as MITRE document MTR99W11, “Integrating The Flight Management System with Air Traffic Control Functions: The Concept of Path Objects.” This publication is available to all on the web site, www.caasd.org.

Applications of Path Objects

Path Object Processor (POP)

To make path objects easier to use there will be a path object processor (POP) that serves the pilot and one that serves the

controller. Initially, these will be interfaces to existing equipment, but eventually they will be fully integrated with the FMS and the ground automation systems.

In the aircraft the POP will function very much like another page in the FMS, similar to today's 'holding' page. The pilot will select the appropriate path object from a menu, and fill in the entries. But unlike waypoints, the data will be simple numbers and named fixes, not latitude/longitude coordinates.

The POP for the controller will help formulate the path object expression for the desired command. MITRE is currently experimenting with POP tools that will help make this task routine.

Air Traffic Control

Aircraft Intentions

An important goal for ATC objectives is to keep the aircraft on a known path. This allows the ground to perform its functions of separation assurance and congestion management. While it is possible to publish many pre-calculated routes and store those in the aircraft's FMS, this only provides a limited amount of flexibility. The use of Path Objects has the potential to permit the dynamic alteration of FMS routes, increasing flexibility while maintaining the integrity of the intent information. Figure 7 shows a set of fixed, predefined FMS routes.

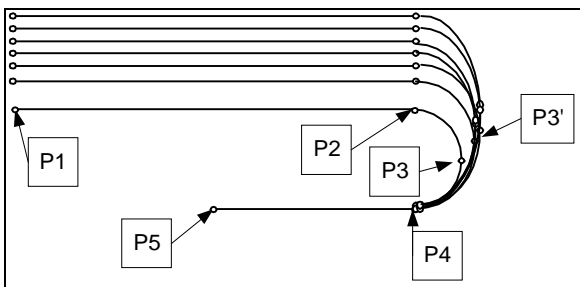


Figure 7. Set of Fixed FMS Routes

With Path Objects a single flexible Path Object, [TP1, **P1**, c, d1, d2, d3], as shown in Figure 8, could generate all of these fixed

routes as well as many more. In this example, the Path Object is defined with parameters that have operational meaning. The length, d1, for example is the width of the *base* leg of the traffic pattern.

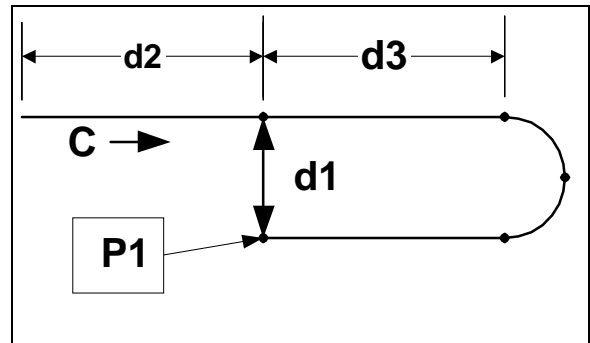


Figure 8. Flexible FMS Routes

Having such a Path Object stored in the FMS would mean that the controller and pilot could communicate in meaningful terms and still keep the FMS in the process of controlling the aircraft's path. This would allow more precise path control even when not all aircraft are equipped with datalink.

By certifying the algorithms in the POP, many variations on FMS-based routes can be created safely, thereby allowing increased flexibility for the ATC system and users. For example, the distance between the downwind leg and the runway can be varied during the day to account for winds and traffic demand. Precise paths can be defined that lead the aircraft all the way to the intercept with the landing aid.

Reduction of Controller Workload

FMS routes, using Path Object technology, can reduce controller workload associated with vectoring aircraft in the terminal area. Replacing vectoring with the ability to select a flexible route reduces the vectoring task to one of issuing only occasional speed adjustment clearances.

As seen in Figure 9 below, there is a decreased workload when using Path Objects rather than vectors. The control system (automated or manual) must issue three

heading changes to instruct the aircraft how to fly an S-turn. In addition, the instructions must be timed so that they are issued when needed to fly the turns. With Path Objects, the control system need only issue one command of the form [PS1, P1, C, a, p] and this can be at its convenience, anytime before the aircraft reaches P1. The control systems on the ground and in the aircraft retain full knowledge about the aircraft's intent.

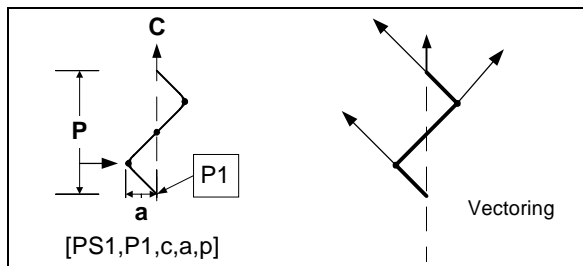


Figure 9. Defining an S-Turn with Path Objects

The Path Object concept offers the capability to add flexibility to the control system while maintaining certainty about the aircraft's intended course. The current system of having paper-based Departure Procedures (DPs) and STARs inhibits flexibility. From the ATC side, it is usually the case that an aircraft must be vectored off the DP or STAR to achieve flexibility. With Path Objects, an aircraft can remain on a path object while its dimensions are slightly varied for ATC purposes. Standardization comes from having a manageable number of types of paths.

Potential User Benefits

Greater Use of the FMS

The FMS offers advantages to the pilot by reducing workload and to the aircraft operator by optimizing the flight profile. However, the requirements for increased flexibility near the airport currently inhibit the ability to take advantage of the FMSs capability. In the future, an automated datalink system will increase the ability to take advantage of the FMSs capabilities.

Because Path Objects are simple expressions, they can be used in a voice environment without data link. Consequently, the aircrafts' FMSs can be gradually brought into the ATC system during the transition from today's environment to the future environment in which every aircraft has datalink all of the time. This will allow a gradual increase in the use of FMS routes in the terminal area and a smooth transition to automation.

Consequently, those operators who enable their FMSs to use Path Objects will get the benefits of reduced workload and increased optimization before datalink is fully implemented.

Pilots will gain increased situational awareness by being on FMS routes, flying familiar patterns, expressed as a simple series of path objects. As controllers and pilots become familiar with these path objects, vectoring will be significantly reduced, if not eliminated.

FMS Database Management

Because path objects are capable of generating many specific routes, the size of the navigation database can be significantly reduced. This in turn has the potential to reduce the costs of collecting, processing, transferring, and storing the FMSs navigation database.

Free Flight Application

The aircraft relies on the ground for separation assurance. Using path objects, the aircraft can quickly and precisely transmit its intentions to the ground for processing. The increased flexibility of Path Objects over pre-stored FMS routes increases the options for the aircraft and increases the flexibility of the whole system.

This technology preserves the free-flight attribute of *freedom of route* by offering flexible arrival and departure routes to ensure that one can always be constructed that closely matches the user-preferred path. It also makes

it easier for the pilot to communicate requests for changes to an aircraft's route.

The use of FMS routes allows aircraft intentions to be known. This will improve conflict probe performance, especially with respect to a reduction in false alerts. Predictable trajectories will enhance safety while affording freedom to choose a preferred route from the many options made possible by the Path Object routing technology.

Inclusion in ADS-B

One emerging cockpit technology, Automatic Dependent Surveillance-Broadcast (ADS-B), involves having suitably equipped aircraft transmit their position, heading and altitude on a *broadcast* channel out to a range of about 200 nmi. Path objects could be used to broadcast the aircraft's intentions in a more precise and detailed manner than by just providing heading information. A simple bit encoding of very common routes could be incorporated within the limited message lengths being planned for ADS-B applications.

Conclusions

Implementing the Path Object concept has the potential to solve many problems that are now facing planners of the world's future ATC systems. By incorporating the aircraft's flight management computer into the architecture of the traffic control system, the Path Object concept offers the capability to maintain a high degree of certainty about an aircraft's intended path regardless of its complexity.

The Path Object concept offers a common language that can express complete information about the aircraft's intended path, which in turn offers benefits to both the ground control system and the aircraft operator. By simplifying the expression of flight paths, it solves many practical problems related to the maintenance of navigation databases, commonality of procedures for the pilot, charting and cockpit display of information, and efficiency of transmission.

Coupled with a universally available coordinate system provided by GPS, path objects can be used anywhere in the world without reliance on ground based navigation aids or datalink.

Path Objects that are defined by parameters having "meaning" to the controller and pilot, such as the length of the base leg, would allow the exchange of intent information even in a voice environment. This then allows the FMS to be incorporated into the ATC system during the transition to a fully equipped datalink environment. Path Object technology offers a solution to the problem of how to deal with partially equipped aircraft which has been a difficult one for automation developers. The concept also can be used during the transition in a mixed-equipage environment using voice and datalink communications.

Path Objects can be slowly integrated into the system over 5 to 10 years as the avionics are replaced and upgraded. To implement this concept, the FMS computers must be enhanced to store and process Path Objects. While this can be done unilaterally by a single avionics manufacturer, an international standard is needed. Both airborne and ground-based POPs must be developed that interface with the aircraft systems and the ground-control systems. In fact, the most advanced FMS systems already have two Path Objects; the line segment and the holding pattern.

While no single benefit of the Path Object concept would probably justify the transition to this concept, the fact that it addresses so many major issues at once, makes it a very desirable concept to both the users of the airspace and the providers of ATC services.