Highly Reactive, Real-Time Planner for Aggressive 3D Aircraft Maneuvers to Avoid Unguided Threats

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This paper presents a technique, Probabilistic Road Map (PRM) planning and its application to aircraft for rapidly generating routes using aggressive maneuvers to avoid incoming munitions, terrain, and other aircraft while trying to maintain other mission objectives. The technique was applied to a high fidelity simulation and shown to always generate correct routes within its 0.1 seconds deadline. Results are presented for several scenarios, some of which are quite complex. Future plans are also described.

Nomenclature

PRM	=	Probabilistic Road Map
PP	=	Path Planner
RPG	=	Rocket Propelled Grenade
UAV	=	Unmanned Aerial Vehicle

I. Motivation

In the course of unmanned and manned aviation operations, emergency situations arise that call for extreme aircraft maneuvers. Hostile enemy fire or impending threat of collision with another aircraft or object may force the choice between executing a maneuver at the maximum dynamic limits of the airframe or potential loss of the system. Emergencies happen suddenly, and a pilot who is fully engaged in completing mission tasks may take a few extra seconds to decide how to react. In this case, there is a clear need for a real time, short term Path Planner (PP) that can generate flight paths that provide maximum deviation from current position and reach an end state that is stable and safe.

For a manned platform with fly by wire flight controls and a sophisticated autopilot, a real time short term PP could be used to automatically avoid one or multiple threats. A pilot may not be comfortable having the aircraft maneuver automatically, so the PP could be used to provide cues to the pilot to suggest the flight path that would provide maximal threat avoidance in such a way that the pilot could manually follow the path.

It is also likely that future combat scenarios will include an increased incidence of hostile threats to unmanned aircraft, and that these aircraft will be fitted with threat detection systems. An automated real time PP that can generate aggressive maneuvers is a natural fit for such an unmanned aircraft fitted with a threat detection system, which will give the aircraft a greater chance of survival. In addition, a real time aggressive PP would be useful for an unmanned aircraft that is flying in coordination and close proximity with other manned or unmanned aircraft.

As autonomy improves and the attack capabilities of unmanned aircraft are improved, aggressive maneuvering will be an asset to an attacking aircraft, including enabling nap of the earth flight to avoid detection on approach to a target. A real time PP coupled with a powerful terrain detection system would be capable of sustaining nap of the earth flight near the dynamic limits of the airframe and physically closer to the terrain than a human pilot would be able to.

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In an emergency situation, valuable time could be saved by presenting the pilot with a flight path that provides maximum threat avoidance while accounting for vehicle states, aircraft rate limits, external safe airspace constraints, restricted operating zones, terrain types, datalink and line-of-sight limits, actions by threats, potential collisions and obstacles in the flight path, and other mission constraints imposed by pilots or air vehicle controllers. For a pilot who has been under a heavy mission workload, the presentation of a good evasive path suggestion could potentially save lives.

II. Description

A. System Overview – High Level Architecture

The context for the PP system is shown in Fig. 1. The same PP software code is relatively straightforward to apply to different aircraft by swapping in each aircraft's configuration information (size/shape, definition of controls, maneuver library, etc.). One of the specific advantages of our approach is the lack of dependency on assumptions and the resulting ability to be easily applied to many different aircraft types and environments. It is also very straightforward to consider a wide variety of constraints. Any constraint that can be expressed as a cost that can be calculated in a volume or while traversing through a volume or be expressed as a volume can be applied.

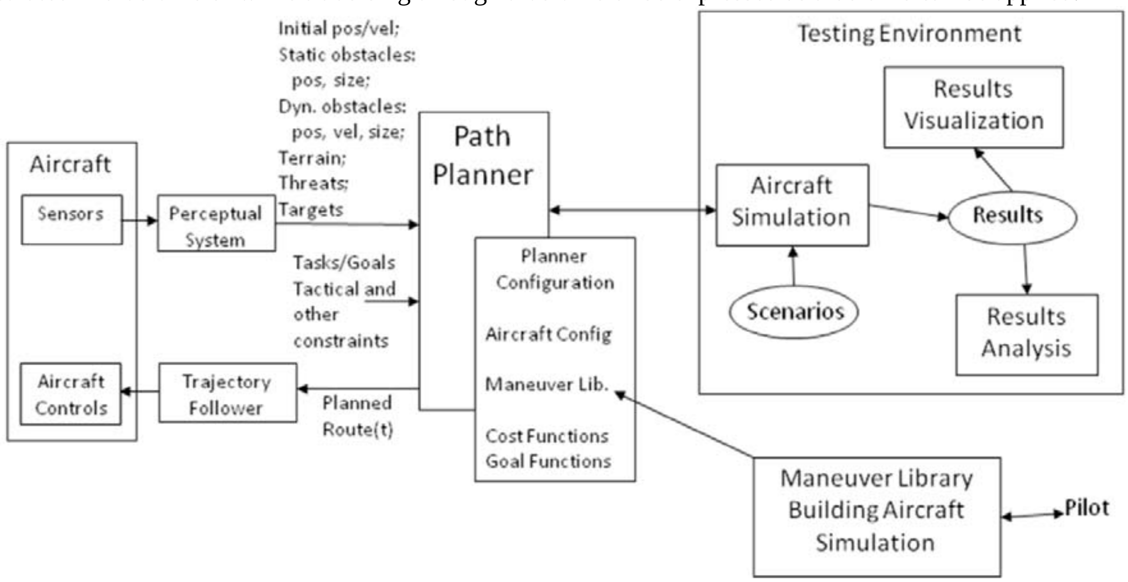


Figure 1. Aircraft Path Planner Context.

The PP is interfaced to the Perceptual System (which is not a focus of this effort), which processes sensor data to determine the static and dynamic obstacles, their sizes and positions, and the velocities of dynamic objects. It passes this information to the PP along with the terrain, threat locations and/or bearings, and target locations. The PP takes this information from the Perceptual System and, along with the current aircraft's tasking, mission objectives, tactical constraints such as maintaining line of sight or relative positions to static locations or moving vehicles or aircraft and considering cost and goal functions, plans a route over time that meets the physical constraints of the aircraft, avoids the static and dynamic obstacles, and reaches a goal point most quickly and in an efficient manner. It then passes back a feasible, collision-free planned route to the aircraft flight control system. Note that although the algorithm computes control settings to determine the feasible path, it does not pass these back, nor expect them to be used by the trajectory follower. The control settings are only used by the PP to ensure that the path is feasible. This decouples the PP from the details of the autopilot.

The described PP represents kinodynamic constraints by combining two methods. One method is to store with each maneuver the pre-calculated state changes caused by that maneuver relative to what would have happened if the maneuver hadn't been executed. These are typically a change in position, a change in velocity, and a change in attitude. (Normally maneuvers are designed to end with constant attitude.) The second method is with the aircraft's equations of motion, which are a set of differential equations that describe the possible local motions of the aircraft, essentially a simulation that calculates the aircraft's motion given a set of control of inputs. Off-line, the simulation is used to precalculate the offsets required by the first method.

The PP builds feasible routes as a tree of reachable milestones. Each milestone has 13 dimensions corresponding to the aircraft's translational and angular positions and velocities, and the time at which the aircraft is planned to arrive at that state. Each milestone represents a reachable state. For each path planning episode, the planner builds a new roadmap (tree of reachable milestones) in the collision-free subset of the aircraft's state-time space, where a state typically encodes both the configuration and the velocity of the aircraft. To sample a new milestone, it first randomly selects a milestone and a maneuver from the library that is appropriate for that milestone's state and then uses the stored delta state values for the maneuver to determine the candidate milestone from the previously generated, selected milestone. By construction, the local trajectory thus obtained automatically satisfies the kinodynamic constraints and structural limits of the aircraft. If this trajectory does not collide with the obstacles, its endpoint is added to the roadmap as a new milestone. This iterative incremental procedure produces a tree-shaped roadmap rooted at the initial state-time point and oriented along the time axis. It terminates when a milestone can easily reach a goal point (a point in a goal volume) without collision. This goal point may be the actual desired final goal state or a milestone on a previously planned route to the goal point. Or the goal state may be implicitly defined to simply meet a number of constraints such as a safe point at the end of a safe route, after all munitions have passed. Furthermore, the goal point, like all milestones will be scored as to a number of positive and negative issues with various priority weights to arrive at a final desirability sum for the goal point.

B. Probabilistic Road Map (PRM) Planner Details

The architecture for the Probabilistic Road Map (PRM) PP is shown in Fig. 2. The dark arrows represent method calls from one component to another, the normal arrows represent data flow, and the dotted lines signify references. The heart of the algorithm is the generation of new milestones and the associated checking that a route has been found. The first step in this process is to select an existing milestone with probability inversely proportional to the density of the other milestones near it. This will tend to favor milestones on the edge of unsampled regions which, in turn, tends to favor sampling milestones in unsampled and under-sampled regions. This typically leads to a uniform sampling throughout the reachable space. Experience has shown that, although one may improve the performance of a PRM planner on some examples by biasing the distribution of milestones, a sampling strategy that yields a uniform distribution of milestones over the reachable free space avoids pathological cases and gives the best results on the average. Also, uniform sampling is required for the proof of the theorem that the algorithm finds a solution if one exists with a very high probability (essentially 100%) for a reasonable space and obstacles. Sampling existing milestones with probability inversely proportional to their density can be approximated with a bin system. The milestone bins are a 4-D array of rectangular boxes corresponding to 3-D space and time. As shown in the figure, any time a new milestone is added to the milestone set, it is also added (in constant time) to the one bin that it corresponds to based on the milestone's location in space and time. To choose a milestone, the algorithm first selects from among the non-empty bins with uniform probability. It then selects one of the bin's milestones with uniform probability, so that milestones in bins with fewer other milestones are more likely to be selected.

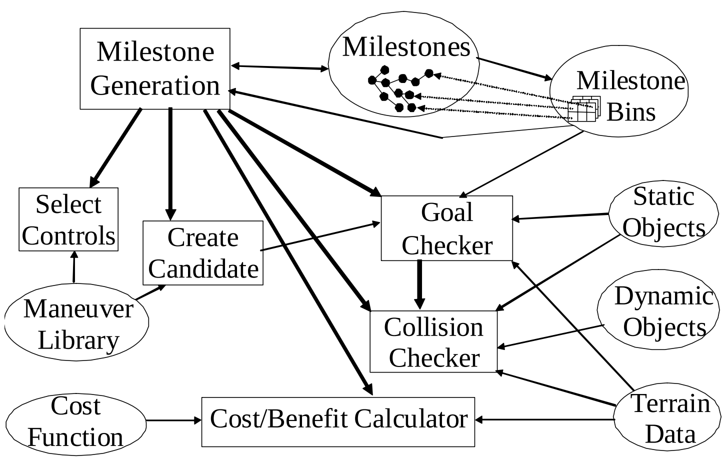


Figure 2. PRM Path Planner Architecture.

1. Maneuver Library Building Software

Prototyping revealed the need to have the maneuver library be created by having real pilots fly the aircraft model and recording their control inputs. To make this process as efficient as possible for the pilots, a maneuver recording facility was added to the FlightLab simulation that stepped the pilots through different initial conditions and requested they fly aggressive and moderate maneuvers with different objectives in mind (e.g., maximum downward displacement, maximum right displacement, maximally up and to the left, etc.). They were also requested to fly the maneuvers such that they ended in constant attitude turns. So the typical maneuver would snap (in the case of an aggressive maneuver) the aircraft rapidly to a new attitude then, using this new attitude, maximally or moderately turn the aircraft with constant attitude in a coordinated way for at least a few seconds. The software could determine how constant the attitude was and to what degree any aircraft limits were violated (e.g., exceeded torque limit by 3% for two-tenths of a second). The pilot could then decide whether his maneuver was adequate and save it or redo it. By having constant attitude turns, the maneuvers are effectively parameterized in time so that the PP by choosing different time periods for the maneuver effectively chooses how much of a turn will be executed (how many degrees the aircraft's velocity vector will change). The software also records how the position, velocity and attitude change compared to the initial conditions. This is used to save several different snapshots at different time instants, which give how the position and velocity are changed by the maneuver, given the length of time that the maneuver will be held. Of course since attitude is constant (after the initial change), the change in attitude is fairly independent of time and is simply the difference between the initial attitude and the final attitude. There is also the facility to request the pilot transition from the maneuver to trim and from one maneuver directly to another (e.g., transition from a turn right and up to a turn left and up). By storing these captured maneuvers from pilots for a variety of conditions, the PP has a large library to draw from. Initial experimentation showed that the maneuvers are fairly robust to changes in flight conditions from when they were recorded to when they were later executed. Typically, for a variety of speeds and loadings (weight and altitude) there should be a variety of maneuvers recorded to turn the helicopter in 8 different directions (up, down, left, right, up and to the left, down and to the right, etc.). While not required, having moderate versions of these turns would be useful for making the path less aggressive when nothing is lost by the moderation.

2. Select Controls

After selecting a milestone, the next step is to randomly select an applicable maneuver from the library, based on the current flight conditions, and instantiate it for a chosen period of time. The maneuver might be interpolated to allow for different flight conditions or slightly different desired types of turn, but neither of these has proven necessary so far (since the maneuvers produced reasonably constant and predictable changes in state across varying flight conditions and the maneuver library was dense enough that the major significant velocity and position vector changes were represented by their own maneuvers). For example, one maneuver to execute an aggressive turn would be to first achieve a maximum roll rate until the desired roll angle is reached. Then, maximally pitch without exceeding the aircraft's limits (which corresponds to a maximum turn rate), possibly accompanied by the appropriate rudder inputs, in order to accomplish a coordinated turn, depending on the design of the specific aircraft. Typically most aircraft can instantaneously change their vertical velocity (i.e., rapidly dive or climb) more than their horizontal velocity (e.g., left and right turns) because they do not need to roll first. For spoiling the first enemy shot, this can be an important factor. The parameter that would need to be instantiated would be the total amount of time/angle through which the turn and/or dive/climb should proceed. An example maneuver in a rotary wing aircraft's library might be a relatively simple one used by helicopter pilots avoiding threats, especially in hover: to throw the collective down (to the maximum amount possible without exceeding the negative G limit of the helicopter) to accelerate maximally downward. The main parameter would be the length of time to continue to maintain the collective at this limit.

The library should contain both the most aggressive turn maneuvers as well as moderate turns and simply maintaining a straight course with various attitudes and velocity vectors. This will allow the PP to maximally change direction to a new heading, possibly including a very steep climb or dive, and then maintain this hopefully optimum course until another aggressive turn is required to either achieve another objective or to defeat another, sequential threat. The end results will tend to be paths that string together maximal turns with other maximal turns or possibly straight line segments in between when threat munitions are in the air.

3. Create Candidate Milestone

The control sequence over time from the randomly chosen maneuver will be applied for a small period of time, delta (which is chosen randomly between the minimum time for the maneuver (to snap to the new attitude) and delta $_{max}$.) (Experiments have found that there is a wide range of acceptable values of delta $_{max}$.). The advantage of storing velocity, position, and attitude changes with the corresponding maneuver in the library is that it reuses the complex calculations that were performed by the simulation using the high fidelity model at the time the pilot executed the maneuver when he was building the library. Instead of recreating these complex, time-consuming calculations, the answer is merely retrieved from storage. The calculation simply involves adding the velocity and position changes to those vectors from the previous milestone in body-centered coordinates and then rotating them to earth-centered coordinates. The attitude change is a simple vector addition.

4. Collision Checking

Collision checking involves three types of objects: terrain, popup static objects (such as wires) and moving objects (such as tracked munitions and other aircraft). The PRM PP, like most route planners, plans the route of the center of the aircraft, assumes that it is very small, and expands the dimensions of all objects and terrain to compensate. So, for example, if the helicopter is modeled as a sphere with a radius of 20 feet, the terrain is expanded by 20 feet and the helicopter is modeled as a point. (Or, if a factor of safety of 2 is desired, the terrain is expanded by 40 feet.) Expanding the terrain 40 feet is not simply a matter of raising it 40 feet. (Consider, for example, a vertical cliff). Each terrain polygon must be moved 20 feet in a direction normal to its surface. The polygons then also need to be reconnected. Fortunately there are standard software libraries for these calculations. Since collision detection must be done on each milestone and each path between milestones, it must be very fast. We used a standard library, which operated extremely quickly, allowing tens of thousands of collision detections and line of sight calculations in a tenth of a second.

Similarly popup objects must be expanded by the helicopter radius as well. Using the 40 foot example, a straight wire becomes a cylinder with a radius of 40 feet (plus hemispherical endcaps). Similarly a 6 foot man suddenly appearing in the landing zone becomes a cylinder with a radius of a little over 40 feet (40 plus the radius of the man) capped with a hemisphere of radius slightly greater than 40 feet. We use algebraic equations to instantly calculate whether milestones or paths between them intersect with these cylinders and hemispheres. When only a small number of popup static obstacles are expected, no indexing scheme is required. However, if a large number will be present it will be more efficient to use a static binning system.

The power of this planning algorithm is in the ability to sample a large number of milestones, so it is important to make sampling each milestone as computationally efficient as possible. If there is a small number of moving obstacles, the route of each can be represented as a second or third order polynomial or as a sequence of linear segments and, in either case, be checked for collision very efficiently. Moving obstacles were represented simply as bounding spheres to limit the computational costs of calculations. This is reasonable for a number of reasons. One is that the moving obstacles primarily represent rotary wing aircraft, which can be reasonably approximated as spheres. Second, it is likely that it is undesirable to have an aircraft pass within the bounding sphere of a moving obstacle, so bounding spheres are not overly conservative.

5. Cost and Benefit Calculation

After the candidate milestone is verified to be reachable, the cost and benefit of reaching it must be calculated. First the cost of traversing from the last milestone to this new one must be calculated. This is highly configurable. The Cost Function for this very small path can consider the type of maneuver and its parameters and the time consumed as well as its energy use or loss and the desirability of the location (from a tactical perspective, or other factors). This cost is stored with the edge from the old milestone to the new one. Additionally the total cost to reach each milestone is calculated from the total cost to reach the previous milestone plus the cost of traversing the path between them and is stored with each. Taken a step further, the desirability of the milestone is also stored with the milestone but separately from the cost. If for some reason, a path must be selected immediately, before a path to a goal point is found, the planner can at least provide the path to the most desirable milestone. Desirability is the weighted sum of how well the milestone meets every mission objective, including survival. If there are munitions in the air, the weight associated with achieving a safe minimum distance from all munitions is very high. But there will be other weights reflecting the relative importance of other objectives depending on the aircraft's mission and role within that mission, such as maintaining communications, maintaining contact with reconnaissance targets, destroying enemy units, maintaining aircraft energy, attacking threats engaging this aircraft, and targeting threats engaging this flight's other aircraft. Any objective or other desirability criteria that can be calculated relatively quickly can be included. Line of sight (LOS) calculations are normally one of the more expensive calculations and we were able to show that even performing many of these at each milestone in was possible within the tenth of a second limitation.

6. Goal Checking

In many of the scenarios, the goal is implicitly defined. This means that any point obeying a number of constraints can be considered a goal point. Normally these constraints primarily define that the point is safe. Generally this means that the point represents a time and state of the aircraft such that enemy munitions and other moving objects (such as other aircraft in our formation) are no longer a threat, the aircraft is in trim, and in its current state it will not collide with anything for at least several seconds. Additionally the desirability of different goal points will be calculated as for any milestone as described above. Typically more desirable points maximize mission objectives and other "good" values and minimize costs or other "bad" factors.

III. Results

The PRM PP was implemented and applied to a rotary wing aircraft, the OH-58D Kiowa Warrior and tested in very complicated scenarios involving a complex sequence of simultaneous shots and popup obstacles where each single episode of simultaneous Rocket Propelled Grenade (RPG) fire events and popup obstacles was rapidly followed by the next episode of simultaneous RPG fire events and popup obstacles. Many of the episodes were explicitly engineered to try to “trap” the helicopter but in each case it was able to find a route solution. For example, in one scenario, the helicopter takes 2 RPG shots in series, both from the right. When a shot is coming from approximately the same altitude as the helicopter, the best maneuver is to dive hard, which sinks 13 ft. in the first second. The first shot causes this to happen, but by the time the second shot is taken the helicopter is too close to the gorge wall to take that maneuver. The next best option from the library is then to climb. However, if a wire is detected ahead and above the helicopter at the time of the second shot, it cannot climb and resorts to a dive-turn maneuver. If another wire is also detected ahead and below the helicopter, it cannot sink either, so it takes a climbing right turn, which climbs and goes to the right (but not high enough to hit the first wire). If a third wire is blocking off this maneuver, the helicopter takes a shallow right turn that ducks under the last wire. This turn stays approximately level with the helicopter's initial course, so it would normally not be a desirable maneuver if a shot is coming from the same altitude as the helicopter, but the planner is forced to choose this route because of the terrain and popup wires (total of two shots and 3 wires).

Most of the 3-D plots are too complex to comprehend on 2-D paper but the plot to the right is relatively simple. The helicopter is proceeding left to right in the plot (shown in blue) when an RPG launch is detected in front of and below the helicopter (shown in red). The threat plane defined by the launch RPG location and the helicopter’s location and velocity is primarily vertical so the PP reacts with a hard, flat, right turn (out of the page).

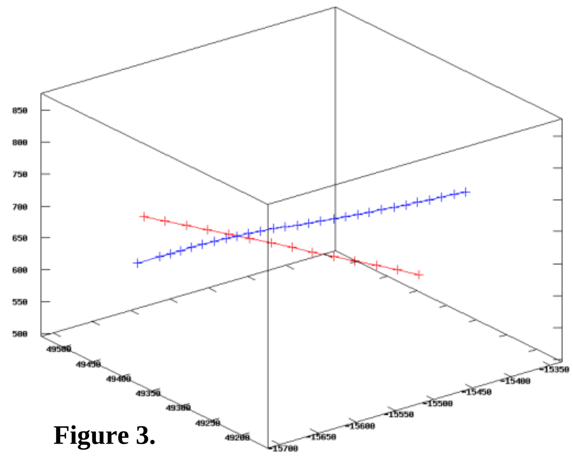


Figure 3.

The helicopter effectively reacts instantaneously to complex sets of obstacles and munitions while maintaining a large number of mission objectives, if possible. No limits were observed and no computational difficulties encountered in the PP’s ability to handle any realistic number of obstacles, objectives, and terrain within its tenth of a second deadline. Its performance clearly exceeded what is possible with human pilots. When the system is seeded with a library of expert pilot input maneuvers, it will be effectively utilizing, in less than a tenth of a second, the best maneuvers an expert pilot would devise given time to think and prepare and possibly redo (during the library building process). This demonstrates the real potential of the system – to leverage the best human capabilities, previously recorded, in a fraction of the time the human could react within real time.

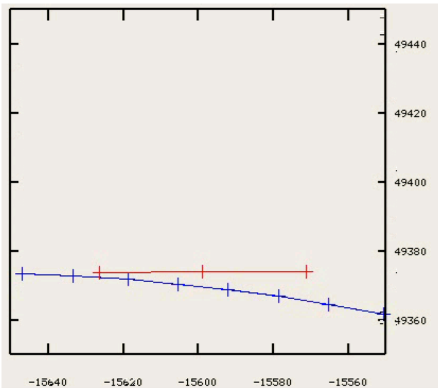
In order to ascertain the approximate accuracy of the predictions as to aircraft state based on the recorded maneuver information, 72 test runs were performed at a variety of speed, which compared the actual position of the helicopter with that predicted, after a 1 second maneuver. The speeds were 5, 10, 15, 70, 80, and 90 knots. (Maneuvers were recorded at 10 and 80 knots.) The resulting errors in position were almost always less than 2 feet. (There were three errors between 2 and 3 feet.) This should be compared to the fact that the helicopter at 80 knots is travelling a total of over 130 feet in that time. These numbers indicate that 20 knots spacing is more than adequate for capturing maneuvers at higher speeds and 10 knots spacing is more than adequate at lower speeds.

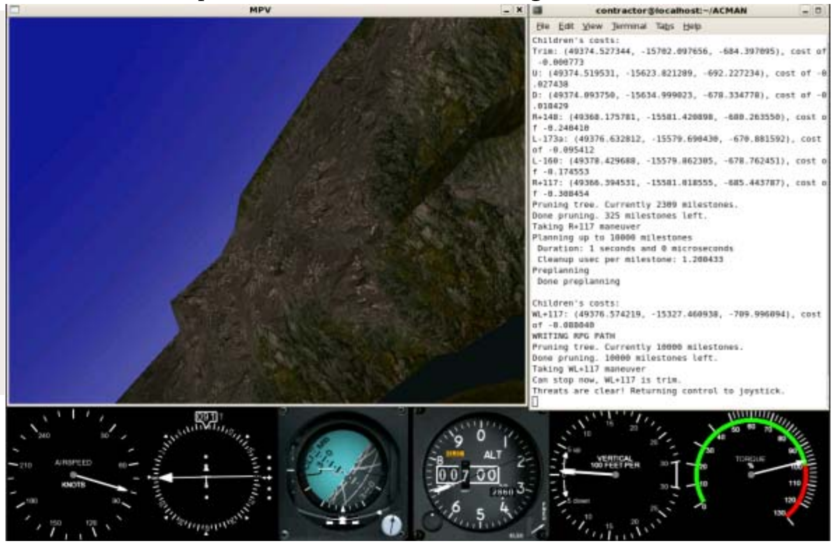
In the 0.1 second deadline that the PP operated within, it always came back with a valid route and typically generated about 2300 milestones. Once in a maneuver, which typically lasted about 1 second, it had the entire maneuver time to plan. It was always able to generate the maximum number of milestones allowed (arbitrarily set at 10,000) and typically planned routes of around 45 seconds in length.

A demonstration sequence was developed that started with simple scenarios and gradually increased in complexity until quite complex scenarios were performed. Many of the scenarios are paired where very similar situations are encountered but the difference forces the planner to plan a different route. This is used to illustrate all the different factors and subtleties that the planner is considering.

A. Simple Shot Avoidance

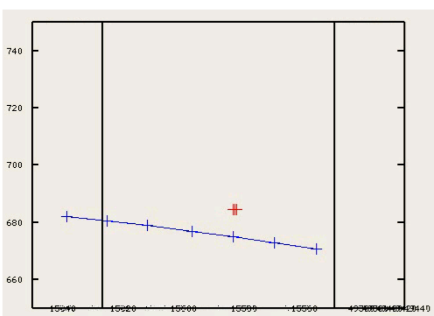
This is illustrated with 3 vignettes. The first one has a shot from in front and below. The shooter, the helicopter and its velocity define a vertical plane of most likely munition trajectories so the best maneuver displaces the helicopter the most sideways. From the maneuver library this is a flat right turn as shown below in the trajectory plot as seen from above with the helicopter flying left to right. Note in the out the window display that the helicopter is banked hard right, its torque is near 100%, and its vertical speed is near 0 so this is a flat right turn.

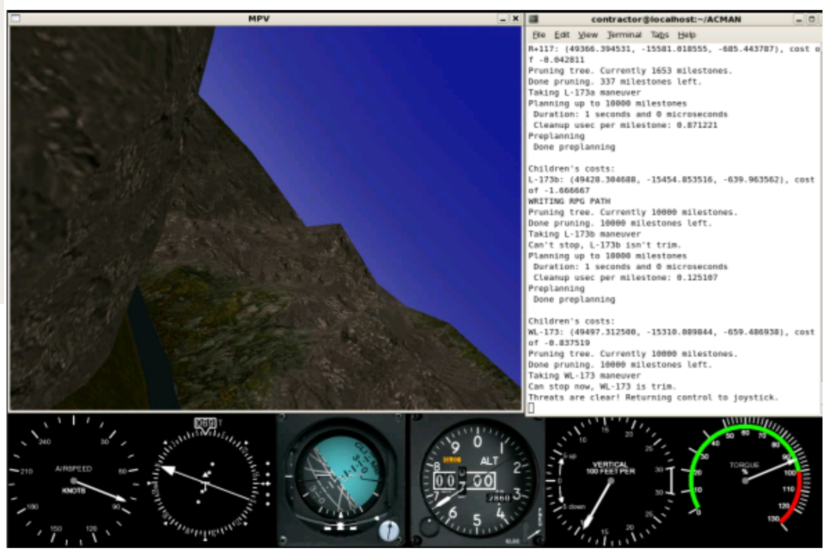




Figures 4 (above) and 5 (right).

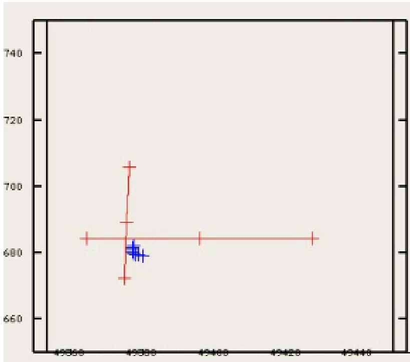
In the next vignette, the shot comes from the right, nearly horizontally so the best course is to drop or climb. The planner chooses a dropping left turn (which drops more than turns). This is shown in the plot, which is viewed from the shooter’s perspective with the helicopter flying left to right. Also note the significant negative velocity on the vertical speed indicator in the cockpit display.





Figures 6 (above) and 7 (right).

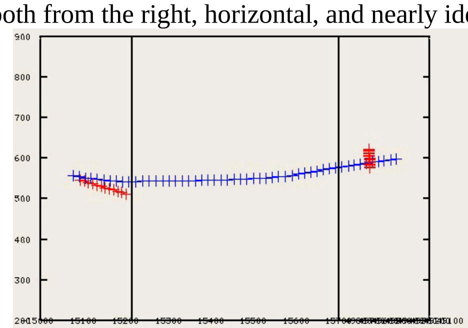
In the third vignette, both shots are taken simultaneously and the best maneuver is neither of the previous two as shown in the plot, which is from the perspective of a viewer that the helicopter is heading directly toward. This is a flat left turn as indicated by the 0 vertical speed indicated on the cockpit instruments.



Figures 8 (above) and 9 (right).

B. Terrain Avoidance

This is demonstrated by a single vignette, which consists of two shots in sequence as shown below. They are both from the right, horizontal, and nearly identical from the helicopter's perspective. The helicopter avoids the first shot with maximum vertical displacement in a dropping left turn as before, but the helicopter is prevented from this maneuver in the second shot by the vicinity of terrain on its left, so it picks the next most vertical displacement, a straight climb as shown in the plot below with the helicopter flying right to left. Note in the plot the initial drop in altitude and then the climb over the second shot. Also note in the screen capture at the end of the vignette, the pitched up attitude in the out the window display and the sharp climbing velocity on the vertical speed indicator.



Figures 10 (above) and 11 (right).

C. Popup Obstacles

There are two vignettes illustrating reaction to suddenly perceived obstacles. The first is a wire that is perceived when the helicopter is 300 feet away. As shown in the plot to the right (with the helicopter flying right to left), the helicopter climbs over it.

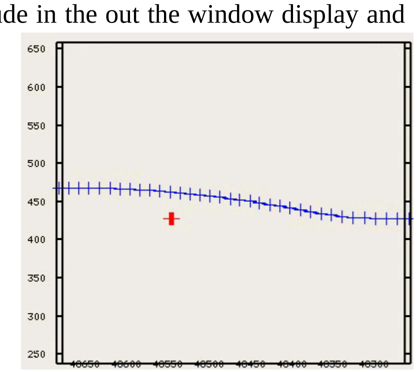


Figure 12.

In the second vignette, the helicopter is set to land on a spot that is 670 feet above sea level as shown in the plot in Fig. 13. However, a 7 foot vertical object suddenly appears on the landing spot when the helicopter is 100 feet away. Keep in mind that the planner will try to stay 40 feet from all objects. The resulting trajectory is shown is the second plot (Fig. 14). Also note the torque on the cockpit display (Fig. 15).

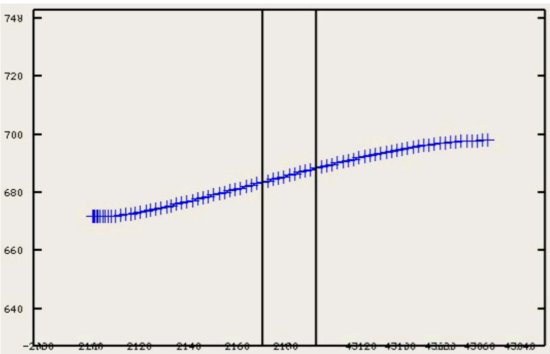


Figure 13.

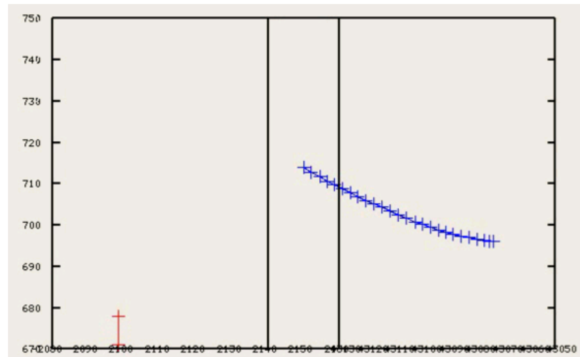


Figure 14.

Figure 15.

D. Build-Up

This was a series of 4 vignettes that used terrain and popup wires to continually restrict the helicopter's ability to maneuver. The base case was the two shot terrain avoidance vignette described earlier. Recall that the second shot required a climb maneuver because terrain on the left side of the gorge prevented the helicopter from any left turn. In the second vignette a wire is added above the second shot as shown in the plot to the right (with the helicopter flying right to left). This wire forces the helicopter to duck under the second shot with a straight dive, instead of climbing over.

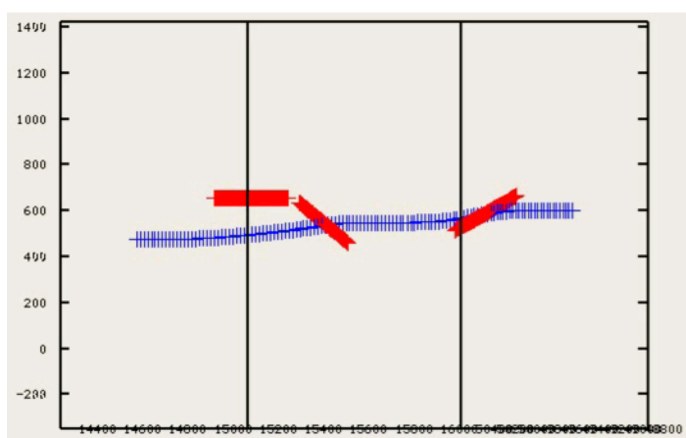


Figure 16.

Then a second wire is added ahead and below, which prevents this straight dive maneuver. Since it can sink, it climbs just enough to go over the second wire and the shot but not enough to hit the wire above. The plot is too complicated to see on two dimensional paper.

Then a third wire is added that prevents even this maneuver. The only maneuver left to it is a flat turn that avoids the terrain and all three wires but doesn't move out of the likely munition trajectory plane very much. But given real obstacles (static or dynamic) it will always choose to maneuver to free space over the theoretical possibility of a munition when there is no choice, which was the case here. The plot is still too complicated to understand but it is presented to the right to give an idea of the complexity that the planner was faced with.

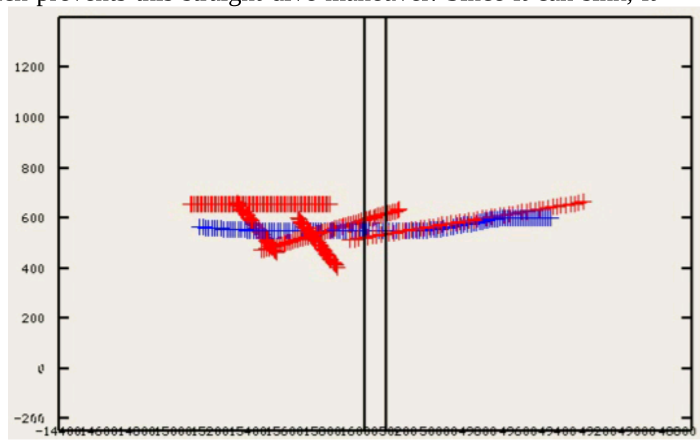


Figure 17.

E. 5 Sequential Shots

In this vignette, 5 sequential shots are taken in a 14 second period to show that the planner can interrupt its current plan to handle new threats. In this vignette, the second shot is taken 6 seconds after the first then the subsequent shots occur more rapidly. The plot is zoomed out to show the entire 14 seconds of flight. As this is almost 200 feet of flight, it is difficult to see the approximately 10 foot separations that the planner achieves on each shot.

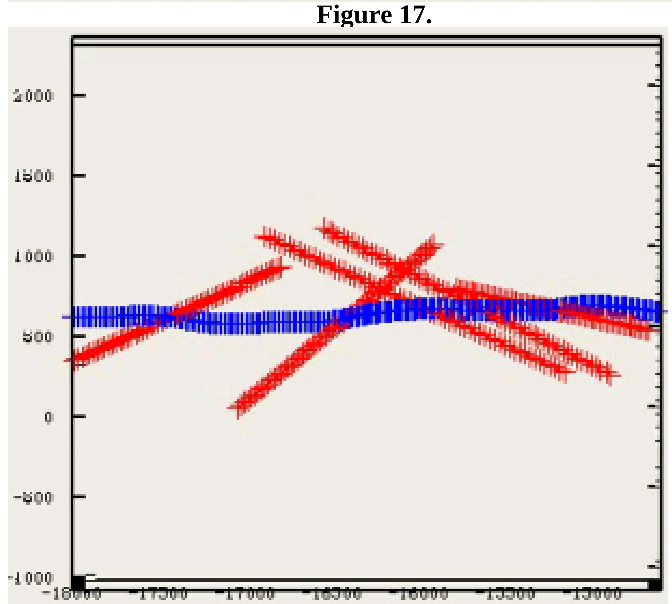


Figure 18.

F. Grand Finale

The purpose of this vignette was to show the complexity that the planner could easily handle. 12 total shots are taken during 5 separate volleys as shown in the plot below.

IV. Future Work

After the PRM PP concept was validated in a prototype with the OH-58D Kiowa Warrior, we began development of the full-scale system for the AH-64D Apache. That airframe is more responsive and maneuverable and, hence, more unstable. Our preliminary results with the Apache have been very favorable from a route planning perspective. Testing the routes has been more difficult. The prototype described above, instead of using a high-quality, third party real-time trajectory follower (autopilot) capable of utilizing the full flight envelope, used the stored control inputs for testing in the simulation with good results. Similarly for the Apache, such a trajectory follower does not exist and the sensitivity of the aircraft has made using the stored control input less reliable that for the Kiowa. We believe that we will be able to correct for some of this unreliability by using interior slices of our transition maneuvers. When complete, we will be comparing the

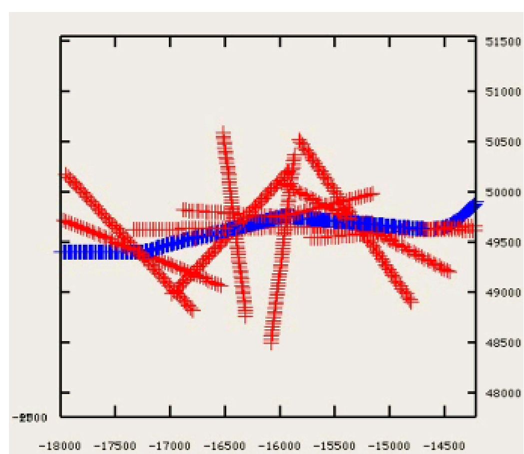


Figure 19.

PP's performance to actual pilots in the same simulated scenarios. We will also experiment with different ways of displaying the routes for human pilots to follow. One promising display technique is to use wire frame "tunnels."

Filling out the full-library of maneuvers need for the full-scale operational PP has been hampered by constraints on qualified Apache pilots' time. We have found that we have been able to populate the maneuver library by tweaking recorded maneuvers with a graphical editor to make them applicable to other conditions.

We have found that moving the PP from the Kiowa to the Apache was as straightforward as expected. To further prove the ease of widely applying the technique we will soon be adapting the system to an Unmanned Aerial Vehicle (UAV).

V. Conclusion

This effort showed that PRM path planning was applicable to aircraft route planning, that highly aggressive routes to avoid incoming munitions could be generated very rapidly with this technique (within less than 0.1 seconds), and that the PRM PP always returned a valid route, no matter how complicated and constraining the scenarios that were thrown at it. Subsequent efforts have also shown that the technique easily adapts to different types of aircraft.