Assured PNT for small UAVs in GPS-denied environments: An outline discussion of battlefield cost-exchange ratios and a comparison to the historic RAF Pathfinder system

The Auto617 team.

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1 Introduction

In this white paper we set out some of the discussions and thinking within our company over almost the last three years since the Russian invasion of Ukraine, and how this impacts requirements for the Position, Navigation and Timing (PNT) of small UAVs (Uncrewed Arial Vehicles) in GPS-denied conditions. As you will see, we find it useful to consider and compare targeting practices from the early years of electronic warfare to find parts of an approach for this very new situation. These discussions have informed product development in our company over the last two years.

This paper begins by examining an early example of best practice in electronic navigation for wartime targeting. The Pathfinder method was developed by the Royal Air Force (RAF) in the period 1942 to 1944. While much has changed, comparing these historical innovations with today's battlefield and economic constraints provides valuable insights into future developments. We then contrast this with the navigational challenges faced by small UAVs today, comparing and contrasting with the challenges of the 1940s. GPS changed everything in the 1990s, but take GPS away, as on the modern GPS-denied battlefield, and we will see that some of the constraints, cost-exchange ratios and solutions start to resemble 1940s ones.

2 The Pathfinder System

The method developed by the RAF in the second half of the war was known at the time as the "Pathfinder Force" (PFF)[1] or simply the "Pathfinder System"[2].

The Pathfinder Force was developed by a team led by Air Vice-Marshal Don Bennett and formally established in 1942. The concept involved a specialized group of highly skilled crews who flew ahead of the main bombing force. Their role was to mark the target area using flares or other markers to guide the following bombers. This typically involved:

- Pathfinders: Aircraft that dropped Target Indicators (TIs), typically coloured flares or smoke markers, to guide the bombing force. TI flares functioned as analogue beacons, creating a coordinate system for target designation under low-visibility conditions.
- Master Bomber: A highly experienced officer who coordinated the bombing raid in real-time, often circling over the target and giving instructions via radio.
- Main Force: The bulk of the bombers who followed the Pathfinders and aimed their bombs at the illuminated or marked target.

This system greatly improved the accuracy of night bombing missions and was a critical innovation in Bomber Command's operations against German targets. A key aspect was that the main bomber force did not simply drop their bombs on any marker flare. Instead, the master bomber would direct the main force not just to a particular flare, but to a target defined with respect to that flare. An example might be "Ignore the green flares and bomb 500 yards north of the blue flare.". Therefore the Target Indicators (TIs) were not really indicating target locations directly, but were providing a coordinate system that the master bomber could use to define the location of a target factory (for example) within the city, even when no flares actually landed on the factory. The Pathfinders often used different colored target indicators to distinguish between correct and incorrect markers. For instance, the Master Bomber might direct bombers to ignore "green" markers and instead aim for "blue" markers if the first attempt was off-target. This flexible use of various markers and pyrotechnic devices allowed the Pathfinder Force to adapt their techniques to different conditions, improving the accuracy of night raids despite challenges like cloud cover or enemy defenses.

Usually the Pathfinder force would use powerful radar navigation aids, such as Oboe and H2S radar[4] to identify and mark targets, especially when cloud cover or poor visibility made visual identification difficult from the cockpit. Oboe was a precision radio navigation system that guided Pathfinders to release markers or bombs at a specific location, while H2S was a ground-mapping radar that allowed bomb aimers to locate targets on their radar screens[3].

2.1 German Countermeasures and Their Failures

Some potential countermeasures to the Pathfinder system are immediately obvious, and indeed the Germans tried hard to frustrate the system, by eliminating RAF flares and introducing fake ones.

2.1.1 Fire Extinguishing Teams

In response to the Pathfinder system the Germans had specialized teams known as "Luftschutz-Flammenlöschkommandos" (Air Raid Fire Extinguishing Commandos) or simply "Flammenlöschtrupps" (Fire Extinguishing Teams). These teams were part of the broader Luftschutz (Air Protection) organization, which was responsible for civil defense during Allied bombing campaigns in World War II. Their specific role was to extinguish or obscure the target markers dropped by Allied Pathfinders to mislead bombers and reduce the accuracy of bombing raids. They were given specialized training to handle flares, Target Indicators (TIs), and incendiary bombs, with a focus on speed and efficiency. As soon as Pathfinders dropped markers, Flammenlöschtrupps would race to the marked location to extinguish or obscure the flares.

In response the RAF simply dropped more marker flares to the point that the Flammenlöschtrupps could no longer cope with them all. The British also used decoys to confuse enemy defenses, dropping dummy markers or setting fires in false target areas. The point being that the dummy markers were far cheaper for the British to deliver than the effort the Germans needed to devote to them, an early example of what is called "asymmetric cost dynamics". These countermeasures significantly reduced the effectiveness of German fire-extinguishing teams. The British strategy of overwhelming, misleading, and adapting rendered it nearly impossible for the Germans to keep up with the volume of markers deployed. This was especially true in the later stages of the war when Allied air superiority allowed for larger, more frequent bombing raids with massive Pathfinder support.

Ultimately, while the Flammenlöschtrupps were a determined effort by the Germans, the British ability to escalate their bombing tactics and technology ensured that the Pathfinder system remained highly effective.

2.1.2 Fake German Flares

The Germans dropped fake flares or ground-based lights in locations away from the actual targets, hoping to confuse the British bomber crews. These markers mimicked the appearance of British Target Indicators (TIs) by using similar colours and patterns. The Germans would deploy these fake flares or decoys shortly after the British Pathfinders dropped their genuine markers, attempting to blend their efforts with the actual targeting.

The British were aware of these deception efforts and took several countermeasures to ensure that their bombing missions remained effective. The Master Bomber, circling over the target area, played a critical role in identifying and directing bombers to genuine markers. By observing patterns and assessing the location of markers relative to known landmarks or radar data, the Master Bomber could issue commands to disregard suspicious markers. The British used specific sequences of colours for their markers during each raid, changing them regularly to prevent the Germans from accurately replicating them. For example, a raid might begin with red markers followed by green ones, confusing the Germans if they attempted to mimic earlier raids.

By the later stages of the war, the sheer scale of Allied air operations and their technological superiority overwhelmed German defenses, including their deception efforts. The use of fake flares became increasingly less effective as the British refined their bombing strategies and technologies.

3 Modern methods of navigation in GPS-denied conditions

3.1 Problem definition

Today's small UAVs face significant threats from electronic warfare. Jamming destroys GPS signals, rendering drones ineffective and forcing operators into dangerous proximity to targets. Published figures indicate somewhere between 30% and 75% of drones are lost due to jamming[1], a new approach is critical for the success of small UAVs on the modern battlefield.

In the three years since the Russian invasion of Ukraine we have seen several key factors that impact the choice of navigation system for small UAVs[6];

- A relatively static front line. This is in large part a consequence of;
- Extremely high-intensity conflict zones. The ever-present threat of UAV swarms on modern battlefields mirrors the operational environment of WWII, where continuous targeting demanded innovative responses. The high density of UAVs, especially First-Person-View (FPV) drones carrying small munitions has made the battlefield extremely hazardous for ground troops.
- There are now two levels of layered airspace control, one above 100m determined by piloted aircraft, and one below 100m determined by UAVs. It is common for one side to have multi-tiered air dominance above 100m and the other below 100m.
- The loss of surprise. Ground troops near the front line know that they are under attack. The density of UAVs is high, and they are often audible by their buzzing propellers. Even if not audible, cheap drone detection electronics available to both sides give an audible warning to troops when active FPV drones are in the area, allowing them to take some precautions against being targeted. But the truth is, if you are close to the front line you *are* being targeted and you know it. This continuous risk has had mental stress effects on many combatants, and exceeds combat stress in earlier conflicts. In every conflict until now an infantryman could protect himself by digging a foxhole. Frighteningly, FPV drones can be directed to fly straight into foxholes.

[1] According to General Pierre Schill, the French army's chief of staff, commenting on the war in Ukraine.[7]

4 A modern target designation system analogous to Pathfinder

So what would a modern *automatic* version of Pathfinder look like, and would it address the key problems? The requirement now is for accurate (perhaps around one metre) targeting using a UAV that carries a much smaller munition than those WWII bombs.

- Pathfinders: A surveillance drone drops a large number of Target Indicators somewhere near the target. It may navigate by rather imprecise means (e.g. inertial guidance). We will not discuss in detail what the Target indicators are in this document, suffice it to say *they each have a location and an identity.*. They are definitely not flares though - more likely electronic transponders or optical markers.

- Master Bomber: A second surveillance drone (or possibly the same one on a second pass over the target) photographs the area around the target, including some or all of the emplaced TI beacons. Returning to base (or transmitting the images there) allows personnel to decide on the targets. The coordinates of those target(s) *with respect to the TIs* are communicated to the UAV attack drone(s).

- Main Force: A UAV, or possibly swarm[5] of UAVs, navigates roughly to the intended target with GPS (where reliable) and inertial guidance (when GPS is not reliable), then uses the Target Indicators to define its location. The target is defined with respect to those target indicators (e.g. "50m north of TI beacon number 671")

In the 1940s it was a function of the Master Bomber to identify and discount fake or moved TIs. In the UAV case, if the *relative* positions of TIs change between the Master Bomber and Main Force steps then they can be automatically discounted by the computer on the UAV. In other words, only those TIs who's relative position has not changed are used to define the target location.

So why has the system not been used since 1945? Probably the battlefields have not been sufficiently toxic to infantry. If infantry are almost always under attack then warning your enemy of an impending attack does not matter. They know they are under attack from UAVs almost all the time. This has typically not been the case - but today it probably is.

There is also a self-reinforcing element to this. If one is expecting a rapidly-moving front line then stealth is a great advantage. One hits an opponent out-of-the-blue if one can. This means the navigational electronics in such a missile are rather more expensive, which in turn means you really don't want to warn your opponent that said missile is on the way (otherwise they will just take countermeasures and the expense is wasted). So expensive missiles need stealthy navigation, which makes them even more expensive and in even greater need of stealth. Now that cheap UAVs are the staple of the battlefields of Ukraine, one could turn this argument on its head. It no longer matters that your enemy is warned of an impending attack because (a) an attack is *always* impending, and (b) if a swarm of six cheap UAVs attack simultaneously from six different directions there is really very little he can do with the prior warning.

5 Technical approaches to navigation in GPS-denied conditions

Before seeing how the economics of this UAV-Pathfinder system might work we consider the other technical approaches possible in GPS-denied conditions, many very successful and most much more expensive. Navigation of missiles and UAVs in GPS-denied conditions is a critical area of research and development, especially for military and strategic applications, at least for small and inexpensive UAVs. However, for the right unit cost (typically more than US$100,000) one can regard it as a "solved problem". A variety of technologies and methods have been developed to address this challenge. These methods often rely on integrating multiple sensors and techniques to provide redundancy and robustness. Key Methods for GPS-Denied Navigation comprise;

5.1 Inertial Navigation Systems (INS)

INS uses accelerometers and gyroscopes to measure motion and orientation relative to a known starting point. Advantages: Independent of external signals, highly reliable for short-term navigation. Challenges: Errors accumulate over time (drift), requiring periodic correction or calibration from other sources. Inexpensive micro electro-mechanical (MEM) systems of the type used as accelerometer in smartphones and car air-bag sensors are *not* sufficiently accurate to direct UAVs in the absence of GPS. Electromechanical INS (sometimes supplemented by star tracking celestial navigation) was used in the first generation of ICBMs in the 1950s, prior to GPS of course, with an accuracy, or Circular Error Probable (CEP), the radius within which a missile is expected to land 50% of the time, between about 1.5km and 10km for the Soviet R-7 Semyorka and American Atlas and Titan ICBMs.

5.2 Visual Odometry (VO) and Vision-Based Navigation

Vision-Based Navigation (VBN), including methods like Visual Odometry (VO) and Simultaneous Localization and Mapping, (SLAM), leverages onboard imagery to determine position and orientation. Cameras (optical or infrared) capture images of the environment, and algorithms such as SLAM process these to determine position and orientation. Examples: Feature matching (e.g., recognizing landmarks, patterns like Apriltags, or specific environmental features). Terrain-relative navigation using preloaded maps or real-time mapping. Advantages: Effective in structured environments with distinctive features. Challenges: Performance degrades in low-light or feature-poor environments (e.g., open ocean, deserts).

5.3 Terrain-Referenced Navigation (TRN)

Compares onboard sensor data (e.g., radar altimetry, LiDAR) with preloaded digital terrain elevation models (DTEMs) to determine location. Advantages: Highly effective in environments with unique terrain features. Challenges: Limited in flat or featureless terrain, requires high-quality terrain data.

5.4 Celestial Navigation

Uses star tracking systems to determine position based on celestial bodies. Advantages: Reliable in clear skies and at high altitudes. Challenges: Ineffective in cloudy weather or during rapid maneuvering.

5.5 Magnetic Navigation

Leverages magnetic field anomalies or pre-mapped magnetic signatures of the Earth to determine position. Advantages: Independent of visibility and external signals. Challenges: Limited by the availability and accuracy of magnetic anomaly maps, vulnerable to magnetic interference.

5.6 Radio Frequency (RF) Navigation

Exploits known RF signal sources (e.g., cell towers, Wi-Fi, or enemy radars) for triangulation or signal-of-opportunity navigation. Advantages: Can function in urban or signal-dense environments. Challenges: Requires access to or knowledge of signal sources, can be disrupted by jamming or interference.

5.7 Acoustic Navigation

Uses sonar or ultrasonic signals for underwater navigation or short-range positioning in air. Advantages: Effective for underwater or confined spaces. Challenges: Limited to short distances and specific environments.

5.8 Atomic Clocks and Precision Timing

Integrates highly accurate clocks with INS to reduce drift and improve navigation accuracy. Advantages: Increases the reliability of time-sensitive navigation systems. Challenges: High cost and complexity of integrating atomic clocks into smaller UAVs or missiles.

5.9 AI and Machine Learning

Deep learning models and reinforcement learning are actively being developed for adaptive navigation, enabling UAVs to recognise and respond to dynamic environments. This may use optical imaging alone, or machine learning algorithms to fuse data from multiple sensors and predict navigation paths in real time. Examples: Predictive algorithms to compensate for sensor drift. Neural networks trained on environmental data for pattern recognition. Advantages: Adaptive and capable of improving performance in complex or dynamic environments. Challenges: Requires significant computational power and robust training datasets.

5.10 Particle Filters and Bayesian Localisation

Combines multiple data sources probabilistically to estimate position and orientation. Advantages: Robust in scenarios with partial or uncertain data. Challenges: Computationally intensive and dependent on accurate sensor inputs.

5.11 Hybrid and Redundant Systems

Combines multiple methods (e.g., INS + vision + TRN) to compensate for the limitations of individual systems[8].

5.12 Emerging technologies

Emerging technologies like quantum sensors[12], advanced AI models, and bio-inspired navigation systems (e.g., inspired by insects or birds) continue to push the boundaries of GPS-denied navigation, offering exciting new possibilities for autonomy and precision in challenging environments.

6 Unit-cost economics

The economics of INS systems are particularly interesting[11] to look at in some detail. The cost of an Inertial Navigation System (INS) varies significantly based on accuracy (CEP), technology, and military grade specifications. Here are some approximate cost ranges:

6.1 Low to Medium Accuracy Systems

These use MEMS-based (Micro-Electro-Mechanical Systems) gyroscopes and accelerometers. They are less expensive and suited for shorter-duration or lower-precision applications. Cost: $10,000–$50,000 per unit.

6.2 High-Precision Systems (e.g., Fiber Optic Gyroscopes (FOG) or Ring Laser Gyroscopes (RLG))

These are used in advanced artillery and military vehicles where high accuracy and resistance to drift over time are critical. They are far more robust and accurate compared to MEMS-based systems. Cost: $50,000–$150,000 per unit.

6.3 State-of-the-Art Military-Grade Systems

Top-tier systems, often used in advanced Western artillery systems like the M777 with GPS/INS integration, or modern Chinese equivalents. These combine GPS receivers, INS, and software for precision guidance. Cost: $150,000–$300,000+ per unit, depending on features and robustness.

Clearly we have a problem, in that the INS system cheap enough for a small UAV is not accurate enough, and the INS system that is accurate enough is not cheap enough. In the case of a small UAV costing less than US$10,000 the *only approach we know that meets both accuracy and cost requirements is a version of the Pathfinder system using Target Indicator beacons.* This removes stealth, and makes it clear to the target that they are being targeted, but as we have seen this information may not be of much use to them on a modern post-Ukraine battlefield.

7 Electronic Warfare, Electromagnetic Screening and Artificial Intelligence

Those of the above methods that do not require RF signals (for example INS or VO) have the advantage of allowing the UAV or missile to be better isolated from Electronic Warfare or focussed EM-beam weapons. In blunt terms the navigation system can be enclosed in electromagnetic screening (essentially a Faraday Cage) to isolate it from EW attack. In early 2024 there were news reports that Ukraine had developed [2] AI methods[9] of VO navigation so as to overcome EW and GPS-denial. Around nine months later, though, it was reported in the same news outlet that AI methods were not yet ready, and that both sides had resorted to fibre-optic guided systems [3] of First Person View (FPV) drones to overcome EW jamming. Fibre-optic guided systems are an incremental improvement on wire guidance, a method that dates back to the 1940s. One of the issues that may be proving a problem for AI in this application is that they can require huge and expensive "training sets" of data, in this case images, to overcome the fact that the battlefield looks different in different lighting conditions, or slightly different compared to yesterday when images were recorded to identify the target, or overcome the addition of spurious features by an opponent. An 80% probability of correctly identifying a tank may be acceptable, but a 20% probability of misidentifying an ambulance as a target is unacceptable. Improving these probabilities to, say, 95% and 1% respectively, under a variety of battlefield conditions is a massive challenge for hardware light enough to be carried by a UAV, and requires massively-expensive training datasets.

[2] https://www.telegraph.co.uk/world-news/2024/04/08/ukraine-developing-unstoppable-ai-powered-attack-drone/

[3] https://www.telegraph.co.uk/world-news/2025/01/10/russia-fibre-optic-drone-ukraine-war/

8 Target Indicators

In the 1940s the target indicators used by the RAF were typically coloured flares. We have seen that the RAF were able to overcome the German attempts to destroy them by simply dropping too many for the Germans to cope with. And attempts to add fake flares were overcome by adding coloured ones.

The Pathfinder or Target Indicator approach has been tried a few times since WWII. British Aerospace experimented with it around the year 2000 [4], concluding that the TIs were too easy for an opponent to destroy or fake. This may appear strange, given that similar German attempts to frustrate the Pathfinder system failed in the 1940s, but perhaps by 2000 some of the autonomous navigation payloads needed were not yet in place. Now they are.

8.1 Does destruction of TIs work?

As we have seen, even in the 1940s the problem of destroying TIs was overcome by simply dropping more of them. On a toxic battlefield, where troops must avoid going out in the open at all costs, searching for and destroying TIs is not possible. Even if it is possible to destroy, say, thirty TIs in an hour before the UAV(s) arrive, then the response is to drop 60. Provided a few survive the attempt to destroy them is unsuccessful. A Bayesian analysis confirms this. Provided (a) the TIs beacons come from a preassigned and known subset of beacons, and (b) the coordinate system defining the target is based on those that have not moved in *relative* position, then only three out of those 60 need to remain unmoved. The enemy can destroy, move or deface 57 of those 60 without having any significant effect on the accuracy of targeting, because changing the position of a TI beacon with respect to others removes it from the set used to define the target location.

8.2 Does faking of TIs work?

Since WWII a whole series of complex coding schemes have been developed for applications in banking or commerce. The RFID chip in your credit card communicates a code to a near-field reader in the coffee shop very reliably, with essentially zero chance of that coffee being charged to the wrong cardholder. Electronic codes and encryption have moved on significantly in the last quarter century, for example with the invention of QR codes and Apriltags that have a unique numerical identity that is extremely impractical to try to forge. This is a much better solution than was available in WWII, where there were only a small number of different coloured flares. As an example, suppose you use as a TI a radio transponder that emits a 16 bit binary sequence in response to a 16 bit binary trigger sequence from the UAV. There are 65,536 different possible combinations for both codes. Your UAV knows what the correct response should be to an arbitrary sequence that it transmits. Any attempt by an opponent to fake the response sequence is, statistically, doomed to failure.

[4] Prof Nick Colosimo, Personal communication

We can conclude that faking and destruction of TIs in the 1940s failed, and with modern methods are even more certain to fail.

9 1944 vs 2025

Clearly the first point to make is one of scale. The RAF in 1944 was attempting to hit factories. A UAV in 2025 is attempting to hit an artillery piece, or a tank, or a mobile radar. In absolute terms we need around 500 times better location accuracy or Circular Error Probable (CEP). The next point to make is about mobility. Factories do not move. A static target is suitable for static TIs. Even at 500 times better CEP, the Pathfinder method will not be applicable to mobile targets like tanks or armoured vehicles. It is easy to move away from the TIs before the UAV(s) arrive. So the method is limited to fixed and semi-fixed targets. Semi-fixed targets may include towed artillery and mobile radar equipment, which although easy to move have an opportunity cost associated with moving them - the time lost that could have been used to fire shells. Given that in a number of potential theatres the western democracies face a large asymmetry of numbers of towed artillery, this case is worth examining in more detail. Overcoming this asymmetry must be an objective for the use of small UAVs in wartime.

9.1 Economics of artillery or radar emplacement relocation

Clearly Target Indicators are good for immovable targets such as HQ buildings, but almost useless for mobile targets like tanks. Consider those assets that lie in-between in terms of mobility. Table 1 shows the best estimates we can find[10] of the time taken to relocate a towed artillery piece by 1km. The differences in time taken are mostly due to the degree of automation of the targeting mechanism that will require calibration and bracketing after each move.

Towed Artillery	**Move 1 km**	**Calibration/Bracketing**	**Total**
Modern Western	10–15 min	1–3 min	11–18 min
Russian	10–30 min	3–10 min	13–40 min
North Korean	15–40 min	10–15 min	25–55 min
Chinese	10–30 min	2–8 min	12–38 min

Table 1: Comparison of artillery system setup and operational times.

Consider a realistic scenario; the commander of a piece of towed artillery is firing rounds at his target. He sees target indicators being dropped around him. From previous experience he knows that this means perhaps a 30% chance that a swarm of 4 or 5 UAVs will attack sometime in the next hour. He has a decision to make, either to relocate the artillery piece or not. If he does not, then its likely it will be destroyed. If he decides to relocate then it will mean an interruption of firing of between 11 and 55 minutes, depending on the technology and training of the unit. Is the interruption of 11 to 55 minutes worth the cost (perhaps US$500) of dropping the TIs for his opponent? Without doubt. In an extreme example, suppose the orders to this commander are to relocate whenever TIs are dropped in the vicinity, to avoid being attacked. Then the artillery piece is rendered useless for a whole day at a cost of US$24,000. This is a very good deal considering the destruction that a day of shelling from this piece can cause.

10 Conclusions

Integration of advanced Assured PNT systems will be critical for maintaining operational effectiveness in highly contested environments. The RAF Pathfinder system of the 1940s demonstrated the effectiveness of precise and adaptable targeting methods under challenging conditions, overcoming countermeasures through innovation and scalability. Applying these principles to modern UAV navigation in GPS-denied environments reveals the potential of updated Pathfinder-inspired methods. By utilizing advanced Target Indicators, automation, and robust technologies such as encrypted codes and visual verification, UAVs can achieve precise targeting of fixed and semi-fixed threats like towed artillery or radar systems. This approach not only counters the high costs and limitations of advanced navigation systems but also disrupts adversaries economically and operationally by forcing frequent relocations or downtime. Ultimately, a modernized Pathfinder system offers a cost-effective, scalable, and highly adaptable solution for UAV targeting on today's complex battlefields. Collaboration between industry and military stakeholders will be essential to implement these solutions effectively.

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