TOWARDS 'INTELLIGENT' CRUISE MISSILES: CONTOURS OF INNOVATION

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As early as 1915, the *New York Tribune* described the progenitor of the cruise missile as "a device likely to revolutionize modern warfare".[1] True to this assertion, almost within a century, cruise missiles have begun to live up to the expectation. There has been significant advancement in the technologies used to construct the airframe, propulsion, penetration aids and guidance system, largely resolving the shortcomings in them. Today, the Global Positioning System (GPS) permits cruise missiles to be guided toward their targets with a level of precision that is measured in feet. Advances in propulsion technology have enabled cruise missiles now to operate at ranges that are transforming them into significant weapons. Also, innovations in stealth shaping and materials have increased their inherent survivability. With an operational pedigree covering seven decades, cruise missiles can now be regarded as "mature and well established technology".[2] The Gulf War and the Kosovo crisis of 1999 amply demonstrated how this piece of technology can revolutionise modern warfare.

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1. *New York Tribune*, October 21, 1915, cited in David J. Nicholls, "Cruise Missiles and Modern War: Strategic and Technological Implications", *Occasional Paper No. 13*, Center for Strategy and Technology, Air War College, Air University, Maxwell Air Force Base, May 2000, p. 1.
2. Carlo Kopp, "Cruise Missile Guidance Techniques", *Defence Today*, http://www.ausairpower.net/DT-CM-Guidance-June-2009.pdf, p. 55.

Certainly, significant technological advances accrued over the past forty years have transformed the cruise missiles into reliable weapons with considerable range, extraordinary accuracy, and a significant degree of survivability.[3] But due to the sheer variety available now (around 130 types) and their elastic and non-sequential evolution, tracing the magnitude of all the innovations accurately is a stupendous task. This article scrutinises only those landmark innovations in cruise missile technology which have transformed them into a state's major component of the combating inventory. Highlighting the modern attributes of cruise missiles, it identifies the current technological innovations that have actually endowed these attributes which distinguished them from their earlier versions.

CONTOURS OF INNOVATION

The attributes of modern cruise missiles are actually the offshoots of the successive value additions in different components of the missile. The journey of this missile, starting from the German V-1 to the hi-tech versions of today, in fact, is the journey of the technological "Innovation Stream"[4] conditioned by the imperatives of modern warfare, the contemporary security environment, and the technological changes occurring. Technological changes broadly constitute: (1) the incremental improvements in performance; (2) architectural advances that result from substitutions of sub-systems that are central to the device's functionality; and (3) the discontinuous or fundamental shift in the underlying technology that represents a leap in overall functionality.[5] Sometimes, the specific requirements of countries demand a specific innovation and the market is always sensitive to this. Therefore, the requirements of the current and emerging customers contribute to the flow of the innovation stream. Countries explore and exploit situations to carry forward their technological inquisitiveness. Of course, this innovation stream poses both organisational and resources related challenges.

3. Nicholls, n. 1, p. 3.
4. "Managing Multiple Streams of Innovation", Change Logic LLC, http://www.change-logic.com/pdf/Managing%20innovation%20streams.pdf
5. Ibid.

As far as missile technology is concerned, the conceptual design of the innovation is most often conducted during the "exploratory development" phase. The *primary objective of exploratory development is to investigate and evaluate technology alternatives* to overcome existing shortcomings[6] (emphasis added). It is not that the existing technical shortcomings require replacement by completely new sets of technologies all the time. In fact, an "enabling technology" alone or in combination can provide the means to generate giant leaps in the performance and capabilities of the existing technology.[7] For example, the coming together of the satellite, telecommunication technologies, computer, Internet, and groupware has revolutionised the capabilities of all other existing systems. The same is the case with the evolution of cruise missile technology. The mid-Seventies saw the rebirth of the cruise missile, as inertial guidance, computer and propulsion technologies reached a level of development which allowed a new generation of these weapons. Subsequent sophistication in the enabling technologies transformed cruise missiles into the most modern and efficient weapon system.

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Most of the advancements that have taken place in the 'enabling technologies' for the operational effectiveness of cruise missiles are related to their navigation and guidance, propulsion or engine technology, warhead and the design or the airframe. The earlier technology and design of cruise missiles mainly comprised a simple mid-course guidance (programmed autopilot or remote/command guidance), a conventional airframe (metal skin structure with conventional aerodynamic flight controls), conventional propulsion (jet propulsion or use of liquid rocket motors), and terminal

6. Eugene L. Fleeman, "Technologies for Future Precision Strike Missile Systems – Missile Design Technology", paper presented at the RTO SCI Lecture Series on "Technologies for Future Precision Strike Missile Systems", held in Tbilisi, Georgia, June 18-19, 2001, http://ftp.rta.nato.int/public//PubFullText/RTO/EN/RTO-EN-018///EN-018-05.pdf
7. "Enabling Technology", http://www.businessdictionary.com/definition/enabling-technology.html

Reverse engineering of German V-1 and V-2 missiles by the US and USSR in the post-War period further evolved the guidance technology.

guidance (either passive radio-frequency homing, radar, or passive infrared for terminal homing).[8] Such designs possessed severe limitations. Mid-course guidance had limited autonomy and accuracy, while propulsion systems produced limited ranges due to poor fuel efficiency (typically 300 km or less). Terminal guidance systems required a "cooperative target", in that the ability to acquire targets at operating ranges beyond 150 km was severely limited by uncertainties in mid-course guidance.[9] Innovations in all these fields have improved the efficiency of cruise missiles gradually. The subsequent sections discuss how different enabling technologies, especially the guidance, propulsion and advanced materials used in the design of the airframe, added value to the earlier versions, thereby enhancing their overall performance.

INNOVATIONS IN NAVIGATION AND GUIDANCE

The basic objective of using a standoff weapon is to launch it from outside the enemy's air defence system to avoid exposing the launch platform to the adversary's retaliation.[10] But to make the missile reliably navigate thousands of miles to the target poses considerable design challenges. The German V-1, the first operational cruise missile, was guided by a gyroscope-based autopilot and an anemometer-driven distance measuring device.[11] This was especially intended for area bombardment of large urban targets like London. Before launch, the missile needed to align to the intended heading and distance, and once the odometer setting on the distance measuring device informed about the weapon arriving over the target, the autopilot would drive it into a steep nosedive. But this technique was inaccurate, with miles of error.

8. Dennis M. Gormley and K. Scott McMahon, "Proliferation of Land-Attack Cruise Missiles:Prospects and Policy Implications", http://ftp.fas.org/irp/threat/fp/b19ch6.htm
9. Ibid.
10. Kopp, n. 2.
11. "Lawrence Sperry: Autopilot Inventor and Aviation Innovator", http://www.historynet.com/lawrence-sperry-autopilot-inventor-and-aviation-innovator.htm#high_3

Reverse engineering of German V-1 and V-2 missiles by the US and USSR in the post-War period further evolved the guidance technology. The US Navy's Regulus series, the US Air Force's Mace/Matador series and the Soviets' KS-1 Kometa and Kh-20 Kangaroo series employed gyro-based autopilots in which radio command links permitted adjustment of the weapon's flight path. During the 1950s, all anti-ship cruise missile guidance was gyro-based, sometimes supplemented by mid-course radio link updates.[12] Terminal accuracy was provided by a compact short-range radar seeker, semi-active in the earliest designs but soon supplemented by active radar designs.[13] The next important innovation in the guidance system came with the Northrop SM-62 Snark intercontinental cruise missile. The Snark introduced a better inertial navigation system, which used a gyro stabilised platform. It also used precision accelerators to measure the vehicle's motion and an analogue computer system to accumulate measurements and locate the vehicle's position.[14]

But the drift in the inertial guidance was very high which resulted in cumulative positioning errors. Every hour of flight accumulated many miles of positioning error. To rectify this problem, another enabling technology, the stellar navigation system or the 'star tracker', was used. This is an automated optical device to measure angular measurements of the device against known star positions and used to calculate the vehicle's position in space.[15] Though it proved a success, its maintenance difficulties and the cost factor prevented this technology progressing further. However, the success of the stellar technique was path-breaking for the satellite navigation technique which was probably the progenitor of the currently used GPS and Glonass system. Satellite navigation experiments initiated during the 1960s were based on a concept similar to

12. "Cruise Missiles of the 1950s & 1960s", http://www.vectorsite.net/twcruz_3.html
13. Robert P. Papadakis, "Joint Vision 2010 and the Operational Commander: Is GPS A Double-Edged Sword?", http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA349297&Location=U2&doc=GetTRDoc.pdf
14. "Northrop SSM-A-3/B-62/SM-62 Snark", http://www.designation-systems.net/dusrm/app1/sm-62.html
15. Carlo Kopp, "Stellar Navigation to Satellite Navigation", http://www.ausairpower.net/DT-MS-0407.pdf

In spite of the progressive improvements in the inertial system during the 1960s, the exorbitant cost of the system raised the debate of accuracy versus cost.

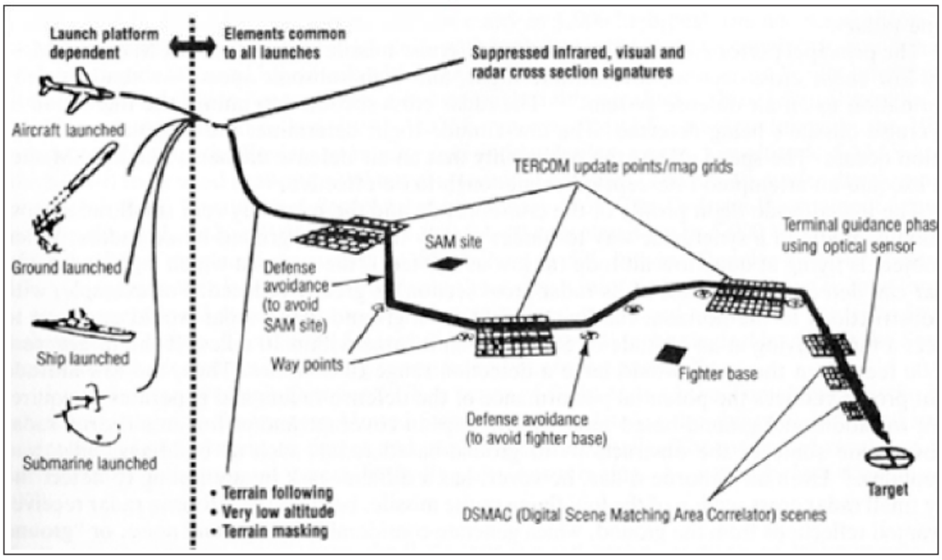
the stellar system, but used polar orbit satellites instead of the stars, supported by natural, light, man-made microwave signals and pseudo-range rather than angle measurements.[16]

In spite of the progressive improvements in the inertial system during the 1960s, the exorbitant cost of the system raised the debate of accuracy versus cost. During the 1970s, this concern led to the next major advance in cruise missile guidance technique – the Terrain Contour Mapping (TERCOM). The technique of TERCOM was incorporated in the US and Soviet cruise missiles during the 1970s and 1980s respectively, to correct cumulative inertial system errors.[17] This technique was a significant improvement against stellar systems since it was compatible with the low altitude flight by a cruise missile. It was relatively cheap to manufacture and highly accurate, down to tens of metres. During its flight, the missile equipped with TERCOM continuously gauges the terrain elevation under its flight path by using a radar altimeter and compares the measured results with a barometric altimeter elevation.[18] The TERCOM navigator mounted on the missile carries a stored digital elevation map of the terrain it is intended to fly over. The elevation curve of the terrain flown over is then compared with the stored digital elevation map by an onboard computer, to find the best possible match. Once the profile is matched to the mapping data, the position can be found within the digital map with good accuracy to correct the inertial system error. Fig 1 shows how the TERCOM system works to guide the missile towards the target.

16. Kopp, n. 2.
17. Michael Dutra, "Strategic Myopia: The United States, Cruise Missiles, and the Missile Technology Control Regime", http://www.law.fsu.edu/journals/transnational/vol14_1/dutra.pdf, p. 70.

18. "The Weapons Tutorial", *Atomic of Bulletin Scientists*, February 1984, p. 38.

Fig 1



Source: Joint Cruise Missiles Project Office

But TERCOM was not without shortcomings. Generating and maintaining precise elevation mapping data of the terrain over which the missile has to fly was challenging. This technique was also ineffective over water, seasonally shifting terrain like sand dunes, and terrain with varying seasonal radar reflectivity like places where snowfall could alter elevation or conceal terrain features.[19] The system represents the most significant challenge for a long-range cruise missile programme. It requires an extensive database of accurate topographic information to use terrain comparison. Sometimes, the technique becomes ineffective as some significant point is unavailable for reference. For example, for Chinese missiles like the DH-10 or CH-10, the TERCOM becomes relatively ineffective in areas such as the South China Sea.[20] Another difficulty with this technique was the storing of enough data in the onboard computer owing to its limited memory. The TERCOM, while enough for the nuclear armed Tomahawk, was not precise to hit individual buildings or structures with a conventional

19. Kopp, n. 2.
20. "Land-Attack Cruise Missiles (LACM) DH-10 / CH-10, Hong Niao / Chang Feng, Dong Hai-10", http://www.globalsecurity.org/wmd/world/china/lacm.htm

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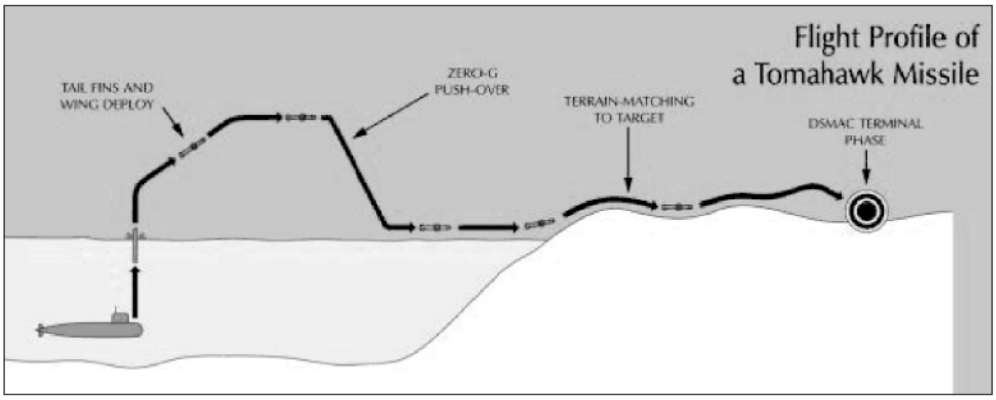
warhead.[21] Therefore, the US Navy supplemented TERCOM in its RGM-109C/D Tomahawk Land Attack Cruise Missile (LACM) with an additional system termed as Digital Scene Matching Correlator (DSMAC) technology:[22] the scene matching correlator technology uses a camera to image the terrain beneath the weapon, and then digitally compares the image with a stored image produced by satellite or aerial reconnaissance. By measuring the rotation and translation required to exactly align the two images, the device can measure the position error of the vehicle very accurately, and use this to correct the inertial and TERCOM errors.[23] Fig 2 shows the flight of a Tomahawk guided by TERCOM.

Fig 2



Source: http://www.scribd.com/doc/14253521/Tomahawk-1

The DSMAC used in several blocks of the Tomahawk was indeed accurate, but produced operational side effects as it was sensitive to seasonal variations in terrain contrast.[24] This problem was sorted out by the

21. Kopp, n. 2.
22. "BGM-109 Tomahawk", http://www.fas.org/man/dod-101/sys/smart/bgm-109.htm
23. Kopp, n. 2.
24. Ibid.

use of GPS. By the 1980s, the GPS receivers were integrated to the cruise guidance system. This allowed the missile to continuously correct its inertial error, regardless of terrain and weather conditions, and worked well over both water and land. But GPS was vulnerable to jamming, as its signal is inherently faint. It was also susceptible to 'multipath' effects where GPS signals are reflected from terrain or buildings. Further, the accuracy of the flight depends on how many satellites are visible at any given time, and how they are spread across the sky. Therefore, during the late 1980s and 1990s, the guidance system became a synthesis of systems constituting the GPS, the inertial guidance package with mechanical inertial technology replaced by cheaper and more accurate ring laser gyro technology. The problems of accuracy of GPS have been progressively addressed by the introduction of the Wide Area Differential GPS technique to overcome the inherent range limits for local-area DGPS service by collecting local-area differential corrections.[25] Then, correction signals valid for a given geographical area are broadcast by radio link to the GPS receiver. For instance, the US cruise missiles used the WAGE (Wide Area GPS Enhancement) embedded in the GPS navigation message broadcast by satellites. This kind of technology could correct GPS errors down to several inches in three dimensions.

The introduction of smart antenna technology, based on 'digital beam-forming' in software, somehow addressed the problem of jamming and multipath. "With this arrangement, the GPS antenna sees the whole hemisphere above the missile, and collects signals from GPS satellites, as well as from the hostile jammers. *The Controlled Reception Pattern Antennae (CRPA) synthesises in software narrow beams which are pointed in space in the direction where the GPS almanac predicts a satellite will be, making the antenna effectively blind in all other directions. The system produces 'nulls' in the antenna pattern which are pointed at jammers to further suppress their effect.*"[26] The latest generation cruise missiles are equipped with the GPS/inertial guidance supplemented by a nose mounted digital thermal imaging device to provide a DSMAC-like capability against fixed targets. Against mobile targets like

25. Gormley and McMahon, n.8,
26. Kopp, n. 2.

a radar or missile battery, they are empowered with suitable software and automatic recognition capability. Lastly, the data links, derived from the JTIDS/Link-16 technology,[27] are being introduced to provide capability to retarget the weapon if a mobile target is moved while the missile is en route; but to detect and retarget such movements requires reconnaissance and surveillance capability. Advancement in missile defence capabilities would pose further problems in targeting the enemy's assets through the available guidance technology but that, in turn, would induce further innovations in the system. However, analysing the trend of the evolution of cruise missile guidance, one can easily visualise that it will be ever "more intelligent, more autonomy, more diversity in sensors, better reliability and lower costs".[28]

INNOVATIONS IN PROPULSION TECHNIQUE

Starting from the V-1, which was powered by a 'pulsejet engine' that gave it its characteristic buzzing sound, to today's supersonic cruise missiles propelled by 'hybrid technology', the missile propulsion technique has undergone many evolutions. Propulsion has evolved from simple pulse jets, through turbojets and liquid propellant rockets or ramjets to the current mix of turbojets for subsonic tactical cruise missiles, turbofans for subsonic strategic cruise missiles and ramjets or mixed turbojet/rocket designs for supersonic tactical cruise missiles. The most widely known pulsejet was the German V-1 missile, or the "buzz bomb", used during World War II, which fired at a rate of about 50 cycles per second.[29] In a pulsejet, combustion is intermittent or pulsing, rather than continuous.[30] The engine admits air through the valves, and combustion is initiated to increase the pressure, closing the valves to prevent back-flow through the inlet. The hot gases are expelled through the rear nozzle, producing thrust and lowering the pressure

27. JTIDS/Link 16 is a combination of systems that are on numerous US and Allied military platforms. It is a kind of network that allows forces to pass a variety of data back-and-forth. "Analysis of the Capabilities and Limitations of Link 16", http://books.nap.edu/openbook.php?record_id=10105&page=151
28. Kopp, n. 2, p. 57.
29. Kenneth P. Warrell, *The Evolution of Cruise Missiles* (Washington D.C.: Air University Press, 1985), p. 42.
30. "The Working of a Pulsejet Engine", http://conceptengine.tripod.com/conceptengine/id17.html

to the point that the valves may open and admit fresh air. A pulsejet engine delivers thrust at zero speed, but the maximum possible flight speeds are below 960 km/h (600 mph). But poor efficiency, severe vibration, and high noise limited its use. Also, the pulsejet could not operate at speeds of less than 150 mph and required a booster and a long ramp for launch.[31]

The American programme that followed with the German V-1 led to very small fuel-efficient jet engines when the designers of the abortive US Navy Gorgon projects had planned to use a jet engine with an outside diameter of only 9 inches. The first American flying bomb experiment was the Northrop Corporation JB-1 series. The JB-1A version started with two General Electric B1 turbojets. A turbojet engine includes "a core engine, an afterburner, and a converging-diverging exhaust nozzle in serial flow communication".[32] The turbofan engines are highly fuel efficient and use a large fan, similar to a jet-engine fan, to move through the air. They offered long-range and subsonic speed with minimal infrared (IR) signature.[33] In the post-War period, Northrop proposed a subsonic turbojet-powered, 3,000-km range missile known as the Snark. The turbojet engine, as used in the Snark and in many later cruise missiles, was a small version of the type of engine used in conventional jet aircraft. It proved very efficient in matters of ranges needed by cruise missiles, particularly when they are accelerated to cruising speed. However, though the turbojet engine provided better speed, it consumed a huge amount of fuel and was capable of very limited range. Subsequently, the Snark missile programme was cancelled owing to the development of its air breathing companion, the Navaho.[34] An interim missile, the XSM-64, used ramjets, using the engine's forward motion to compress incoming air. But ramjets could not produce thrust at zero air speed[35] and, thus, could not move the device from a standstill.

Thereafter, very small fuel-efficient jet engines had started in the US and by 1962, the Williams Research Company had produced the WR-2, an

31. Ibid.
32. "Supersonic Missile Turbojet Engine", http://www.freepatentsonline.com/7424805.html
33. "Military Jet Engines", http://engines.fighter-planes.com/jet_engine.htm
34. "Navaho SSM-A-2", http://www.astronautix.com/lvs/navssma2.htm
35. "Ramjet", http://wapedia.mobi/en/Ramjet

Both the turbofan and turbojet propulsion systems are most suited for subsonic cruise missiles, providing high efficiency to deliver a warhead at long range against non-time-critical targets.

engine that delivered 70lb of thrust which was used to power small target drones such as the US MQM-74. By 1967, the WR-19 engine had demonstrated a thrust of 430lb for a weight of only 68lb and a fuel consumption of .7lb per hr per lb of thrust.[36] Also, further improvements in propulsion took place with the use of advanced fuels such as Shelldyne. Though it is much more expensive than conventional fuel, Shelldyne H has 33 per cent more energy per unit volume than JP-4 and could give improvements in range for the cruise missile of about 10-20 per cent.[37]

Both the turbofan and turbojet propulsion systems are relatively mature technologies for precision strikes. They are most suited for subsonic cruise missiles, providing high efficiency to deliver a warhead at long range against non-time-critical targets. However, the use of the turbofan is advantageous in that it provides better fuel consumption than a turbojet, with a reduced infrared signature.[38] Most of the early variants of the cruise propulsion system were liquid fuelled. But this created many related problems that crippled the missiles' operational capability. First, the large volume fuel tank occupied a very large proportion of the mass of the vehicle, whereby the centre of mass shifts significantly rearward as the propellant is used; this results in loss of control of the vehicle when the centre mass gets too close to the centre of drag. Second, liquid propellants are subject to slosh, which has frequently led to loss of control of the vehicle. Third, liquid propellants can leak, possibly leading to the formation of an explosive mixture. Four, liquid propellants are subject to vortexing within the tank, particularly towards the end of

36. Rajesh Kumar, "Tactical Reconnaissance: UAVs Versus Manned Aircraft", http://www.fas.org/irp/program/collect/docs/97-0349.pdf, March 1997.
37. George N. Lewis; Theodore A. Postol, "Long-Range Nuclear Cruise Missiles and Stability", *Science & Global Security: The Technical Basis for Arms Control, Disarmament, and Nonproliferation Initiatives*, 1547-7800, vol 3, issue 1, 1992, pp. 49–99.
38. Carlo Kopp, "The Strategic Cruise Missile", Part I, *Australian Aviation*, September-November 1985.

the burn, which can result in gas being sucked into the engine or the pump cryogenic propellant such as liquid oxygen freezes atmospheric water vapour into very hard crystals. This can damage or block seals and valves and can cause leaks and other failures.

It is pertinent to point out that ramjets differ in operation from both pulsejets, as used in the V-1, and from turbojets, such as employed in the Snark. The ramjet engine takes in air through a choke or diffuser in the inlet, which slows down the airflow and increases its pressure. The air is then mixed with fuel and continuously ignited by means of a spark-plug. The resulting combustion produces a jet of hot gases in the tail-pipe which react against the enclosed forward parts of the engine to generate a steady thrust. The 1950s saw different versions of the same missile using pulsejets, turbojets or ramjets. But subsequent experiments aiming at long-range started to enhance the engine capability, and thereby, the Modern Ramjet Engine (MRE) was developed. For example, in 1973, there was a perceived need to extend the range of the Phoenix missile because of enhanced threat capabilities. The MRE employed an IRR engine and, since it would require manoeuvring for the anti-air mission, it incorporated two cheek-mounted two-dimensional inlets and had bank-to-turn controls, the same as an airplane. The MRE concept used an integral rocket booster for vehicle acceleration to the ramjet takeover speed.[39]

In the USA, in the early 1970s, the Generic Ordnance Ramjet Engine system was developed through engine testing at NAWC/CL (Naval Air Warfare Centre/China Lake). The configuration chosen was a parallel rocket and annular ramjet. In the mid-1970s, a number of propulsion systems were being investigated for a long-range anti-air missile. Consequently, both solid-fuelled and liquid-fuelled ramjet engine development and demonstration programmes were initiated at NAWC/CL. The performance goals for both were to fly 150 nautical miles (nm) at a cruise speed of more than Mach 3. In the early 1980s,

39. Paul J. Waltrup, et al., "History of Ramjet and Scramjet Propulsion Development for U.S. Navy Missiles", http://www.scribd.com/doc/6097480/History-of-Ramjet-and-Scramjet-Propulsion-Development-for-US-Navy-Missiles

Today, the propulsion unit of a cruise missile employs all the available and upgraded engines of the turbofan, pulsejet, turbojet, ramjet or solid fuelled rockets.

following successful semi-freejet engine tests of these missiles, a second-generation integral rocket, liquid-fuelled ramjet long-range air-to-air missile was developed for the Advanced Air-to-Air Missile (AAAM) system.[40]

In 1982, the US Air Force began studies for a new cruise missile with low-observable characteristics after it became clear that existing cruise missiles would have difficulty penetrating future air defence systems. The solution adopted was to incorporate various low-observable (stealth) technologies into a new Advanced Cruise Missile (ACM) system. The first test missile flew in July 1985 and the first production missiles were delivered to the US Air Force in 1987. The end of the Cold War led a major cutback in total ACM procurement. In all, 461 missiles were ultimately produced.[41] Another propulsion technique comprises the composite motor cases. Composites provide reduced weight compared to a steel motor case. It is viewed that the emphasis on reduced observable plumes will continue with high emphasis in the foreseeable future.[42]

Today, the propulsion unit of a cruise missile employs all the available and upgraded engines of the turbofan, pulsejet, turbojet, ramjet or solid fuelled rockets, each making a different category with different advantages and shortcomings. For example, the French Exocet missile, which is solid fuelled, designed to attack large ships, is very fast but of short range and with a significant IR signature.[43] The Chinese C-802 or the Yingji-82 missile powered by a turbojet engine is supersonic. Due to the missile's small radar reflectivity, low attack flight path (only five to seven metres above the sea surface) and the strong anti-jamming capability of its guidance equipment, target ships have

40. Ibid.
41. http://www.onwar.com/weapons/rocket/missiles/USA_AGM129.html
42. Eugene L. Fleeman, "Technologies for Future Precision Strike Missile Systems – Introduction/ Overview", paper presented at the RTO SCI Lecture Series held in Atlanta, USA, 23-24 March 2000.
43. "Exocet AM.39 / MM.40", http://www.fas.org/man/dod-101/sys/missile/row/exocet.htm

The Chinese C-802 or the Yingji-82 missile powered by a turbojet engine is supersonic.

a very small chance of intercepting the missile.[44] However, the engine consumes a lot of fuel and has limited range. The turbofan US Tomahawk missile is highly fuel efficient and quiet. It offers long range and subsonic speed, with minimal IR signatures. The Block IV (TLAM-E) is the latest improvement to the Tomahawk missile family with advanced capability such as: (a) increased flexibility utilising two-way satellite communications to reprogramme the missile in flight to a new aimpoint or new pre-planned mission, send a new mission to the missile en route to a new target, and missile health and status messages during the flight; (b) increased responsiveness with faster launch timelines, mission planning capability aboard the launch platform, loiter capability in the area of emerging targets, ability to provide battle damage indication in the target area, and capability to provide a single-frame image of the target or other areas of interest along the missile flight path.[45] Lastly, the Russian SS-21 with the ramjet engine requires a booster to flow air at supersonic speed to take on further propulsion.

The design of the cruise propulsion depends on the mission the system is assigned for. The first consideration of the system design for the liquid propulsion system is to decide which type of propellant to use for the specific type of mission. The most obvious advantage of the liquid propulsion system, as compared to its solid counterparts in general, is thrust management and control. Some missiles use both solid and liquid propellant for effective functioning. For example, the BrahMos has a two-stage propulsion system, with a solid-propellant rocket for initial acceleration and a liquid-fuelled ramjet responsible for sustained supersonic cruise, thereby competent for longer range.[46] An important aspect of the development of a cruise missile propulsion system is the use of a new generation of jet fuels – synthesised liquid

44. "C-802", http://en.wikipedia.org/wiki/C-802
45. "Tomahawk Cruise Missile", http://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=1300&ct=2
46. http://www.brahmos.com/home.php

The cruise propulsion system has graduated manifold and will continue to evolve in the future.

hydrocarbon fuels which increase the range of these missiles approximately 15 per cent over that attainable with conventional military and commercial aviation fuels.[47] Also, very small, efficient jet (turbine) engines which have very low-specific fuel consumption have been designed.

The cruise propulsion system has graduated manifold and will continue to evolve in the future. For example, the Advanced Missile Propulsion Technology (AMPT) programme of the US Air Force aims to provide the products, services, and development required to support AMPT. The desired technologies span all areas of application for Solid Rocket Motors (SRMs), including ballistic and space boost, post-boost propulsion and tactical motors.[48]

INNOVATIONS IN THE AIRFRAME

The aerodynamic design or the airframe of the cruise missile which is responsible for the overall performance of the device has undergone many changes over the years. The airframe technology and designs have become progressively more compact to accommodate internal and external carriage by aircraft, launch tubes on warships or torpedo tubes in submarines. The composing materials, the composite structure, insulation materials, the shape of the device and stealth capability have constantly been improving to achieve the real purpose of the cruise missile.

In the domain of airframe materials technology, mainly five new enabling technologies have been innovated: (1) hypersonic structure materials; (2) composite structure materials; (3) hypersonic insulation materials; (4) multi-spectral domes; and (5) reduced parts count

47. G.W. Burdette, H.R. Lander, J.R. McCoy, "High-Energy Fuels for Cruise Missiles", *Energy*, vol.2, no.5, September-October 1978.
48. "Advanced Missile Propulsion Technology (AMPT)", https://www.fbo.gov/index?s=opportunity&mode=form&id=368ba3589e27404a0c700bdbce57461b&tab=core&_cview=1

To penetrate strategic air defence in depth, cruise missiles have to evade all defence mechanisms.

structure.[49] Since the low cost cruise missile is designed to fly at subsonic speeds, the aerodynamic design of the airframe is made with fibreglass reinforced with phenolic resins containing hylon, silica, graphite or carbon and Kevlar composites, mainly to reduce radar profile.[50] Coatings containing finely ground ferrites also offer some degree of radar absorption. The heat signature of the engine could be significantly reduced by judicious entraining of slipstream air to dilute and cool the jet exhaust prior to ejection behind the craft.

The composite materials are of new technology that finds increased use in new versions of cruise missiles and are good candidates for lighter weight insulation.[51] High temperature composites have particular benefits for hypersonic missiles, providing weight reduction. Titanium alloy technology also enables lighter weight missiles in a hypersonic, high temperature flight environment.

Six new enabling technologies in the field of missile aerodynamics are promising to extend cruse missiles capabilities. These are aerodynamic configuration shaping, lattice tail control, split canard control, forward swept surfaces, bank to turn manoeuvring, and flight trajectory shaping.[52] The tailored-lifting-body missile has higher aerodynamic efficiency (lift-to-drag ratio) with enhanced manoeuvrability that is appropriate for extended range cruise performance. Lattice fins are effective for lower hinge movement and higher control at the supersonic Mach number.

To penetrate strategic air defence in depth, cruise missiles have to evade all defence mechanisms. By reducing the infrared signature emitted by the engine, the missile can minimise the chances of its detection by enemy radar.

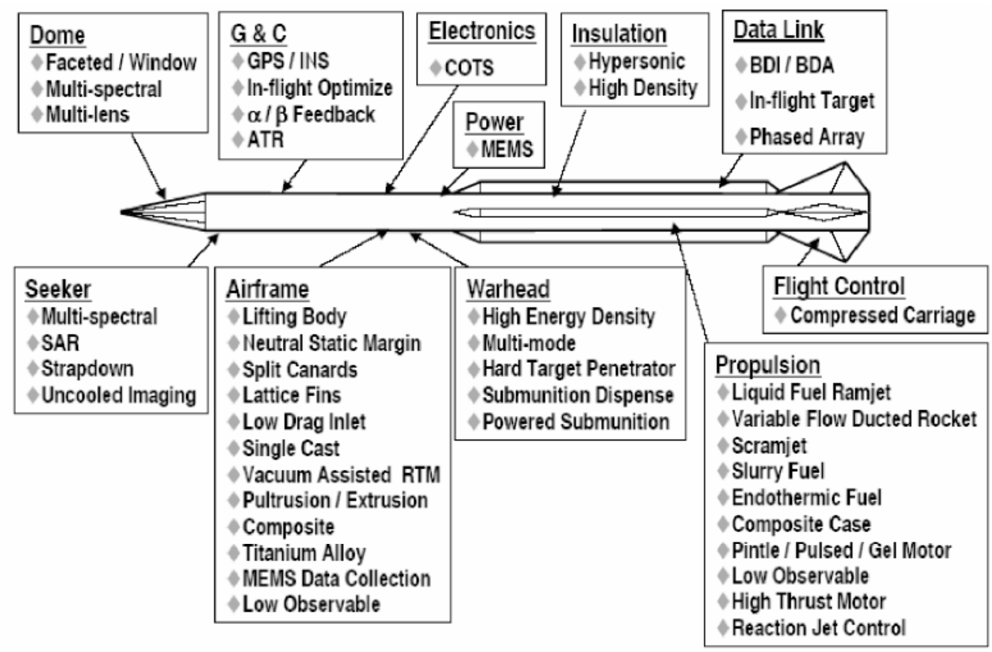
49. Ion Dinescu and Mihaela Oprescu, "Technologies for Future Precision Strike Missile System", The Annals of "Dunarea De Jos", University of Galati, Fascicle IX Metallurgy and Materials Science, Air Force Academy, Henri Coanda, Brasov, 3003, p. 26
50. Bruce Simpson, "The Low Cost Cruise Missile: A Looming Threat?", May 20, 2002, http://www.aardvark.co.nz/pjet/cruise.shtml
51. Dinescu and Oprescu, n. 49.
52. Ibid., p. 24.

Present-day airframe design and the materials used have considerably enhanced its stealth capability. Penetration aids emerged during the 1960s as air defence systems evolved to greater potency, with low altitude terrain following or sea skimming flight profiles to hide missiles from radars and, increasingly, stealth shaping and materials to deny acquisition and tracking by air defence radars. Some Soviet cruise missiles were equipped with track-breaking defensive jammers to defeat interception by air defence missiles. For example, in 1982, the US Air Force began studies for a new cruise missile with stealth characteristics after it became clear that the AGM-86B Air-Launched Cruise Missile (ALCM) would soon be too easy to detect by future air defence systems.

The AGM-129 Advanced Cruise Missile (ACM) delivers the proven effectiveness of a cruise missile enhanced by stealth technology when the threat is deep and heavily defended.[53] Its external shape is optimised for low observable characteristics and includes forward swept wings and control surfaces, a flush air intake and a flat exhaust. These, combined with radar-absorbing material and several other features, result in a missile that is virtually impossible to detect on radar. Its stealth features are apparent: the nose is sharply pointed with sharp edges or chines, reminiscent of the chines used on the SR-71 Blackbird; the missile's wings are swept forward at 26 degrees, again to reduce reflections back to a radar transmitter/receiver forward of the missile; its turbofan engine exhaust consists of a 2D nozzle. It is in a 2D shape to allow the hot exhaust to rapidly mix with the cool surrounding air to reduce the overall IR signature. The inlet is mounted flush with the fuselage to reduce its Radar Cross-Section (RCS), and the missile is constructed with radar-absorbing materials and structures. Fig 3 lists all the new technologies for precision strike missiles.

53. "AGM-129 Advanced Cruise Missile [ACM]", http://www.globalsecurity.org/wmd/systems/acm.htm

Fig 3



Source: http://ftp.rta.nato.int/public//PubFullText/RTO/EN/RTO-EN-018///EN-018-$I.pdf

TOWARDS 'INTELLIGENT' CRUISE MISSILES

Technological innovations are always purpose-driven though they create a demand for themselves, subsequently leading to demand-driven adaptations. As specific purposes or objectives change, demands for new technology propel further innovations. For example, Hitler's objective was to target the entire city of London, therefore, random firing of V-1 missiles served his purpose even though they were not accurate in targeting. Today's warfare warrants targeting of an individual or a particular building/ bunker. Also, sometimes a state has to wage a war within its own borders. Therefore, the shape of the battlefield has undergone surprising alterations and, thereby, the choices for weapons. One classic example is the use of the Israeli short-range AGM 142 "Hav Nap" cruise missiles by the American commanders which could fly directly into the mouths of the caves sheltering Osama bin Laden's forces

Due to the cost, the imperative now is to improve the single shot kill probability of a missile to a certainty.

in the Tora Bora mountains of eastern Afghanistan.[54] To fight such wars, more intelligent weapons are in demand. The cruise missile is perhaps the first kind of modern weapon which is constantly striving to reach the target by conveniently evading all surveillance.

This stream of cruise missile evolution is ongoing and it will continue to move forward in the decades to come. Due to the cost, the imperative now is to improve the single shot kill probability of a missile to a certainty. With the innovations in the different fields of missile technology, the cruise missile as a "smart weapon" is fast becoming a "brilliant weapon" or an "intelligent weapon" that can manoeuvre, recognise and reach pin-point to the target. With advances in artificial intelligence, the deployment of "Intelligent Agents" (IA) has improved the performance of the missile and decreased the 'miss-distance' (the distance between the target and the closest point of approach of the missile) to a small value.[55] The IA is an autonomous entity which observes and acts upon an environment and directs its activity towards achieving goals. As a cooperative problem solver in a multi-agent environment, it negotiates by exchanging information with other agents to solve a problem.[56] In a conventional missile guidance system, from the launch to the time when terminal homing takes over, signals from ground-based radar are received and processed by the receiver unit onboard the missile. The signal environment can be hostile if jammers are present. Therefore, in modern missile systems, intelligent agents are interconnected to generate counter-moves in the hostile environment. For example, to overcome jamming, modern cruise missiles install the digital thermal imaging devices that interconnect the GPS/inertial guidance to provide DSMAC-like (Digital Scene Matching Area Correlator) capability. Many such intelligent agents are in use these days for appropriate counter-moves relevant to different phases of the missile's flight.

54. Sean Rayment, "'Intelligent' Missile Used Against bin Laden Caves", December 16, 2001, http://www.telegraph.co.uk/news/worldnews/asia/afghanistan/1365479/Intelligent-missile-used-against-bin-Laden-caves.html
55. V.Krishnabrahmam, N. Bhardwaj and K.N. Swamy, "Guided Missile with an Intelligent Agent", *Defence Science Journal*, vol 50, January 2000, p. 25.
56. V.V.S. Sarma, "Intelligent Agents", *Journal of IETE*, vol. 42, no. 3, 1996, pp. 105-109.

The cruise missile evolution trend seems to be moving from aid to autonomy.

Generally, conventional cruise missiles are either track-in on some sort of signal or fly to a pre-determined point: there is no situational awareness of decision-making capability in the "end game" or no independent call as to whether or not to press "the kill". Subsequent innovations in the missile sub-systems have gradually infused some sort of decision-making power in the machine, whereby cruise missiles as "smart weapons" have fast become "intelligent weapons" that can manoeuvre, recognise and reach pin-point to the target. Therefore, the cruise missile evolution trend seems to be moving *from aid to autonomy*. Samuel Penn has categorised missiles into six categories according to their operational attributes (Table 1). But today's cruise missiles seem to imbibe all the novel features of previous versions and are constantly striving to become more *intelligent*. For example, the Thirsty Sabre missile can conduct a smart search of the area for targets, and once identified, kick out one of several munitions before moving on to the next target. The Tactical Tomahawk acts like a spy plane which can fly around the target area, give commanders a bird's eye view of the battlefield and then be re-programmed for new instructions. The German Taurus KEPD 350 smart penetrator system is capable of recognising already destroyed structures and counting floor levels of the buildings it attacks.

Table 1

Manual	**Homing Missile**	**Smart Missile**	**Brilliant Missile**	**Clever Missile**	**Genius Missile**	***Intelligent Missile***
Very basic missile.	Locks onto its target using very simple criteria, such as heat signature or nose.	Remote controlled.	Capable of homing in on a designated target.	Capable of making its own choices about targets.	Capable of selecting a target based on many criteria, using strategy to select not only the best target, but also the best route to the target.	Smart + Brilliant + Clever + Genius

Manually guided, being controlled remotely by an observer with a simple joystick. No guidance system of its own. Uses the heavy weapons skill of the controller.	Once fired, the target cannot be changed. They can be confused by sending out decoys.	The observer must maintain control until the last moment. No intelligence itself.	Designation is by a human operator, but after the missile is fired, no further designation is required (unlike for a smart missile). May use a number of techniques for recognising the target, but mostly based on visual or signature recognition.	Once a target is selected, it is capable of following that target itself without outside aid. It actively recognises its target, does not rely on a simple criteria such as heat for tracking.	Capable of working together in swarms, deciding between themselves how to divide up the targets, and changing targets as conditions change. Contra-grave genius missiles have the capability to lie in wait for targets, dodge counter-measures and generally behave like living attackers.	

Source: Samuel Penn, "Yags (Missiles 1.3), 2007", www.glendale.org.uk/yags/articles/missiles.pdf

The Taurus stealthy missile navigates through GPS guidance and an infrared seeker with visual displaying capabilities. The latter scans the overflown terrain at pre-defined checkpoints for possible variances from the pre-set course in order to correct its flight path. The system is designed as a standoff weapon against high value and heavily defended targets and can deliver its explosive power with an extremely high accuracy.[57] Depending on the type of target, several different detonation sequences and final target approach tactics can be applied. For underground bunkers, the Taurus can

57. "German Stealth Cruise Missile Enters Service", http://www.strategypage.com/htmw/htairw/articles/20060402.aspx

attack in a nosedive to maximise the penetration depth. Less hardened targets will be engaged in an extreme low level flight to minimise the danger of detection. Therefore, this millennium seems to be the age of "intelligent missiles" and the current innovations have begun to suit the requirements of modern warfare: for instance, the US Intelligent Missile Project aims to develop techniques for embedding rule-based artificial intelligence system in the US Navy's missiles.

The key parameters in the fabrication of any cruise missile are its standoff range, its accuracy and its survivability against target defences.

The key parameters in the fabrication of any cruise missile are its standoff range, its accuracy and its survivability against target defences.[58] With advanced research and ongoing experiments, the cruise missile would be equipped with more advanced features. At the general level, further innovation in cruise missile technology is likely to drive down the total cost. The aim in the future would be to improve the reliability by accepting some increase in the unit costs, but, at the same time, reducing the number of devices required to complete a given mission. Second, improved miniaturised engines and new fuels can be expected to decrease the power plant/payload ratio. Third, advances in IR detector design seem likely to produce important operational improvements. In particular, the number of IR detector elements that can be fitted within an IR seeker head is being dramatically increased. Fourth, the continuing trend in micro-miniaturisation of electronics increases computational densities that have been produced over the recent years. For example, in the mid-1970s, it was possible to fit about 1,000 gate-arrays or the equivalent of seven transistors into a device measuring one quarter of an inch square. By the early 1980s, the capacity had been increased by a factor of four, and by 1985, a device only one-third larger could hold no fewer than 19,000 gate-arrays. In the last decade, computing power, using these and other devices, has increased by a factor of ten and the volume required has been reduced by a factor of six. This continuing

58. Kopp, n.2, p. 55.

This implies that no matter how sophisticated the technology, the issue of effective air defence would always remain.

process of increasing computational density has very important implications for the operational functions of the future cruise missile and in particular for the physical size of the payload. Lastly, a significant field is stealth technology which is likely to play a major role in the future of air warfare in general and the cruise missile in particular. There is constant effort to innovate Radar Absorbent Materials (RAM) to reduce RCS. Together, the micro-miniaturisation, guidance and stealth techniques will to play a formative role in deciding the place of cruise missiles in the broader spectrum of air power.

With the advances in the defence mechanism and the technology used in specific missiles, chasing of an incoming missile has become possible. For example, the DSMAC used in several blocks of the Tomahawk, though it proved accurate, produced operational side effects during the 1991 Desert Storm campaign. During the operation, for the effective manoeuvre of the Tomahawks towards the selected targets, a number of Baghdad freeway intersections were used as referencing points, which actually allowed Saddam's air defence troops to set up gun batteries and shoot down a number of Tomahawks. This implies that no matter sophisticated how the technology, the issue of effective air defence would always remain. The very characteristics which made the V-1 a headache for British air defence planners in 1941, present the same broad issues for contemporary air defence system planners even though the technology of cruise missiles today is vastly superior to that of the early years. But what has changed between the earlier and current versions of the cruise missiles is the upgraded technology that has given the weapon radically increased capabilities.