August 19-22, 2013, Boston, MA
AIAA Guidance, Navigation, and Control (GNC) Conference

Advances in Inertial Guidance Technology for Aerospace Systems

Robert D. Braun[1], Zachary R. Putnam[2], Bradley A. Steinfeldt[3],
Georgia Institute of Technology, Atlanta, GA, 30332

and

Michael J. Grant[4]
Purdue University, West Lafayette, IN,47907

The origin, evolution, and outlook of guidance as a path and trajectory manager for aerospace systems is addressed. A survey of theoretical developments in the field is presented demonstrating the advances in guidance system functionality built upon inertial navigation technology. Open-loop and closed-loop approaches for short-range systems, long-range systems and entry systems are described for both civilian and military applications. Over time, guidance system development has transitioned from passive and open-loop systems to active, closed-loop systems. Significant advances in onboard processing power have improved guidance system capabilities, shifting the algorithmic computational burden to onboard systems and setting the stage for autonomous aerospace systems. Seminal advances in aerospace guidance are described, highlighting the advancements in guidance and resulting performance improvements in aerospace systems.

Nomenclature

$\mathbf{a}_T$	= Thrust acceleration vector
D	= Drag
f_1	= Proportional gain
f_2	= Derivative gain
f_4	= Integral gain
g	= Acceleration due to gravity
H	= Altitude
m	= Mass
v	= Velocity
$\mathbf{v}_g$	= Velocity-to-be-gained vector
$\mathbf{Q}$	= Gain matrix
R	= Slant range
T	= Thrust magnitude
$(\,)_0$	= Reference value

I. Introduction

THE objective of guidance is to modify the trajectory of a vehicle in order to reach a target[1]. The guidance system takes in information regarding the state of the vehicle and interprets it to produce commands to alter the

[1] David and Andrew Lewis Professor of Space Technology, Guggenheim School of Aerospace Engineering, AIAA Fellow.
[2] Graduate Research Assistant, Guggenheim School of Aerospace Engineering, AIAA Senior Member.
[3] Graduate Research Assistant, Guggenheim School of Aerospace Engineering, AIAA Student Member.
[4] Assistant Professor, School of Aerospace Engineering, AIAA Member.

subsequent trajectory. Prior to the twentieth century, rockets were used in an unguided manner to support conflicts. Early devices included incendiary missiles and fire lances by the Greeks as early as 4 B.C.[2] and flame-throwing devices by the Chinese around the year 1000[3]. In the 1800s, efforts focused on improving the accuracy of rockets in a passive, unguided manner. During the early 1800s, William Congreve, a British army colonel, developed a stick-guided rocket which served as one of the earliest attempts to improve the accuracy of rocket-based weapons[4,5]. In 1839, William Hale developed a stickless rocket with improved accuracy using rotary motion created by directing part of its exhaust flame through slanted exits[4,5]. Near the end of the nineteenth century, Wilhelm Unge, a Swedish military engineer, developed a spin-stabilized rocket in which the spin was achieved by rotating the launcher as opposed to using the angled thrust of the rocket itself. This, in addition to his performance enhancements, enabled 5-mile ranges with accuracies that rivaled rifled artillery.

During World War I, thought was again given to the accurate delivery of weapons. Initially, this was accomplished by firing rockets from steel tubes attached to the wing struts of biplanes[4]. In this environment, the pilot served as a means of providing guidance to the initial direction of the rockets by flying in a constant direction toward the target[4]. In 1918, Charles Kettering developed the first guided unmanned air vehicle, the Kettering Aerial Torpedo (also known as the “Bug”). The Bug was a propeller-driven biplane with a speed of 120 mph and range of 75 miles. The guidance to the target was provided by a system of onboard pre-set, vacuum-pneumatic and electrical controls which, after a predetermined number of engine revolutions, would shutoff the engine, release the wings, and cause the vehicle to dive to the target with 180 lbs of explosive. This served as one of the first vehicles in which an onboard calculation (number of engine revolutions) was used to influence its trajectory based on day of flight conditions (wind speed and direction as well as distance to the target) [4,6]. In World War II, the German V-2 rocket incorporated an onboard guidance system, the LEV-3, which consisted of an accelerometer and two gyroscopes[7]. The accelerometer enabled onboard computation of the engine cut-off time while the gyroscopes allowed for stabilization of the vehicle during flight. As such, the LEV-3 is the first instance of an inertial guidance system used onboard an aerospace vehicle. This concept fundamentally improved the accuracy with which guidance systems were able to reach the target, providing a self-contained system to meaure the position and orientation of an object relative to a known initial inertial condition.

This paper provides an overview of inertial guidance systems and a survey of guidance development for three aerospace applications: (1) short-range systems, (2) long-range systems, and (3) entry systems. For each of these applications, the impact of onboard inertial navigation is discussed showing the resulting improvements in accuracy.

II. Guidance Systems

The goal of guidance is to compute the command required in order to reach a desired target. In aerospace systems, guidance is used in conjugation with navigation and control systems to provide commands such that the target is reached. Schematically the implementation of a guidance, navigation, and control (GN&C) system is shown in Figure 1.

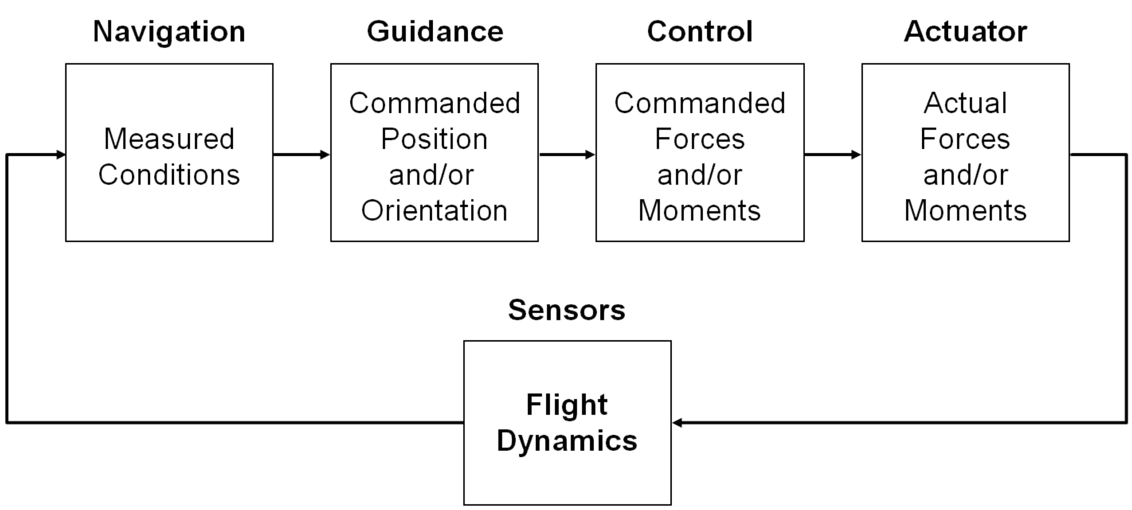

Figure 1. Example guidance, navigation, and control loop.

As shown in Figure 1, the guidance algorithm takes in measured conditions from the navigation system and in turn commands a desired position and/or orientation of the vehicle in order to achieve the desired objective. Consistent with most historical terminology, this paper uses the term "guidance system" to refer to the combined navigation and guidance systems; whereas, "guidance algorithm" refers only to the methods used to command the position and orientation of the vehicle.

A. Categories of Guidance Systems

Passive guidance uses an external source to detect the target and compute the associated command to reach the target[8]. Alternatively, active guidance uses onboard navigational sensors to detect the target and compute the command to reach the target. Passive guidance systems have good performance but can be prone to tracking errors. Active guidance generally results in improved performance, but requires onboard sensing capabilities. With the advance of computer technology, active systems generally rely on more frequent updates of the system and target's states.

Open-loop guidance systems do not take into account information regarding the actual flight dynamics of the vehicle when computing the commands for the system. Instead, the vehicle flies a scheduled set of commands. Conversely, closed-loop guidance systems sense the vehicle's state and alter the guidance commands appropriately. Open-loop guidance algorithms are often simpler and easier to test and implement. Because they do not account for uncertainties in the operating environment, vehicle performance, or target, open-loop systems generally result in reduced accuracy[0]. Since closed-loop systems receive information regarding these uncertainties in flight, their accuracy is generally improved; however, their implementation is significantly more complex.

One can further classify closed-loop guidance algorithms based on their computational sophistication. Model-based guidance attempts to predict the future dynamics based on onboard models using updates to these models obtained in flight by the navigation system. On the other hand, reference path guidance attempts to follow an *a priori* defined reference path or paths[9-11]. Generally, reference path algorithms are less computationally intensive than model-based algorithms; however, a large number of reference paths may need to be stored to span the potential flight envelope. Model-based guidance solutions are comparatively expensive to obtain, but can generally accommodate a larger range of initial conditions and inflight uncertainties.

B. Advancements in Inertial Navigation and Guidance

The first practical inertial guidance system was developed for the V-2 rocket. Since then, a number of inertial navigation systems have been developed. Vehicle orientation was frequently monitored through the use of gyroscopes of various forms including systems that monitor a spinning mass, the vibration of linear momentum, nuclear spin orientations, and laser wave patterns[12,13]. Each subsequent system was designed to improve the monitoring of the angular motion of the vehicle by improving the accuracy of rotating components or removing rotating components completely.

Linear acceleration was frequently monitored through the use of accelerometers of various forms. Early inertial navigation systems were appealing since many were capable of integrating the accelerations mechanically (based on the deflection of suspended masses) to compute velocity[13]. Advances in microelectronics in the 1960's enabled a shift from these mechanically-based computations to calculations onboard a flight computer. This enabled a shift from perturbation techniques to explicit guidance equations capable of utilizing external data such as azimuth data from star sensors and state information from radar systems to update trajectories during flight. This conversion from physical processes to mathematical calculations also enabled the construction of simplified, strapdown inertial measurement systems[14]. After 1964, new platforms were also developed to enable high-g operations which allowed a ballistic missile to be guided throughout the trajectory, including re-entry, as opposed to only during the boost phase[12].

After this time, research efforts focused on improving the accuracy of long duration flight systems. This was accomplished by advancing the state of the art in both inertial navigation systems and onboard guidance computing. During the late 1960s and early 1970s, the typical inertial navigation system error was approximately 1 nmi/hr. To reduce this error build-up during long duration flights, an electrically suspended gyroscope was proposed in 1976 capable of reducing this error to 0.2 nmi/hr[15]. During the 1980s, stellar-inertial guidance systems were shown to be useful in desensitizing target impact errors to initial position error. This was especially attractive for mobile systems with uncertain locations as well as combat-ready systems that could be stored in a dormant or semi-dormant mode to reduce operating costs[16]. Without this feature, traditional inertial measurement performance data had to be continuously monitored for performance anomalies[17].

During the 1980s, advancements in accuracy were also realized from improved onboard guidance models. Earth's angular velocity vector, launch site gravity and astronomical coordinates, and target and launch site inertial velocities had been historically treated as constant. Developments of higher-order gravity models as well as improved pole position models enabled trajectory accuracy improvements of approximately an order of magnitude[18,19]. Flight of the Space Shuttle provide a means for testing high-precision inertial navigation systems in the relevant load and velocity environment. Additionally, zero-g data was obtained to analyze low-g performance[20].

In the 1990s, to reduce cost, a nongyroscopic inertial measurement unit was proposed that consisted of a triad of accelerometers mounted on three orthogonal platforms rotating at constant angular velocities[21]. This arrangement enables the measurement of both linear and angular accelerations. To further reduce cost and complexity, a gyroscope free strapdown inertial measurement unit was proposed in 1994 using six linear accelerometers arranged in a tetrahedral manner. While the error buildup of these simplified systems are much higher than that of a medium accuracy, gyroscopic-based system, the proposed configuration would be capable of covering short mission duration segments that correspond to high angular accelerations and require fast reaction times[22]. Additional improvements have been made in power, size and performance of inertial navigation (e.g., microelectromechanical systems) and onboard guidance systems.

III. Short-Range Systems

A. Guidance Methods for Short-Range Systems

Regardless of whether or not the system is active or passive, the algorithm to compute the command to steer the system towards the target can be divided into three categories: line-of-sight, pursuit, and proportional navigation[8]. Each of these is graphically shown in Figure 2.

(a) (b) (c)

Figure 2. Graphical depiction of (a) line-of-sight, (b) pursuit, and (c) proportional navigation guidance[8].

As seen in Figure 2, line-of-sight guidance continuously points the tactical system towards the target. This implementation is relatively insensitive to noise; however, for moving targets it is inefficient and potentially may not reach the target. Pursuit guidance predicts where the target will be at the next instance in time and leads the vehicle slightly ahead of that target. Finally, proportional navigation is largerly based upon the instantaneuous direction of the target relative to the vehicle and its perceived velocity[1].

B. Early Guided Tactical Systems

Tactical systems are those whose effects are smaller and have relatively small ranges (<500 km). While precision has always been an important attribute of tactical weapon development, the need for the development of guided tactical systems (or guided munitions) was first recognized during World War I as airplanes became more important war fighting machines[23-27]. Following development through the 1930s, the first guided tactical system was put to use during World War II. In March 1943, the G7e/T4 Falke acoustic-homing torpedo was put into service aboard German U-boats[28]. 400 m after being fired, the Kriegsmarine passive acoustic homing system activated onboard the torpedo which was used to guide the torpedo towards sounds[29]. While only deployed in small scale, the G7e/T4 led the way for the mass deployment of the G7es/T5, known to the Allies as the German Naval Acoustic Torpedo (GNAT)[28]. The US successfully sank a German U-boat with a passively guided torpedo system two months later with the Mark-24 acoustic-homing torpedo[30]. Unlike the G7E/T4, the Mark-24 was fired from a PBY-5 patrol aircraft. Paralleling guided underwater tactical weapon development, guided air tactical weapons were developed in the early 1940s and included a series of glide-missiles and guide-bombs such as the television-guided Robin, the radio-guided azimuth-only (AZON), and the semi-active radar homing (SARH) Pelican[4,31]. In 1945, these programs culminated in the active radar homing BAT. Developed by the Naval Bureau of Ordinance in partnership with the Massachusetts Institute of Technology, the BAT (as seen in Figure 3) was gyrostabilized and used an elevator to alter its range to try to reach the target found from the onboard radar[31,32].

Figure 3. U.S. Navy BAT guided bomb on the wing of a PB4Y-2[33].

In 1942-43, the growing Allied air threat led to the German development of a guided anti-aircraft rocket. The rocket was guided from the ground using a control stick. An automated system was also partially completed in which steering signals from a tracking radar would be sent to an onboard analog computer. To further increase onboard autonomy, an optical proximity fuse was also developed to explode the warhead at the point closest to the target[4]. Late in World War II, the US became increasingly concerned regarding its vulnerability to aircraft-launch guided missiles[28]. As such, Project Bumblebee developed the infrastructure necessary to detect and defend against these attack—radars, surface-to-air missiles (SAMs), and combat information centers. The Tartar, Terrier, and Talos naval SAMs resulted from this development effort. Like the Pelican, each of these employed SARH guidance systems[28]. SARH exploited the fact that almost all detection and tracking systems consist of radar, so it is not necessary to carry this hardware on the missile itself. Instead, a larger radar on the ground (or later on launch aircraft) would provide the source signal and target-tracking logic while the missile listens for the signal reflected from the target and then aims towards that reflected source[34]. This is schematically shown in Figure 4.

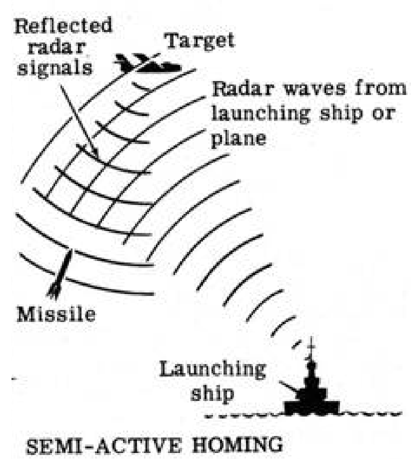

Figure 4. Semi-active radar homing[35].

C. Increasing Accuracy through Better Knowledge

While the systems on which they were fielded changed, the guided munitions fielded through the early 1970s relied on the same basic homing guidance techniques. The first operational air-to-air missile, the AIM-4 Falcon was deployed in 1956 used SARH (and later infrared homing); however, the missile was unreliable and not consistently accurate. As a result, it lost favor to more traditional (unguided) air-to-air missiles[36]. In Korea, the VB-3 Razon and VB-13 Tarzon guided bombs were deployed. Both the Razon and Tarzon were radio-controlled by an airman aboard their B-29 launch platform and were capable of providing delivery accuracies of 300 m[37,38].

The first time that guided munitions precipitated a change in U.S. air-to-ground operation strategy, was during the Vietnam War. During Operation Linebacker, laser guided Paveway bombs began to changed the way precision guided munitions were deployed[39,40]. In order to target these devices, an airman targeted a laser designator to identify the target. This target information was used onboard to control aerodynamic effectors on the bomb in order to reach the target. As shown in Table 1, this precision targeting provided delivery errors of less than 125 m[39].

Table 1. Guided bomb accuracy improvement with conflict[38].

War	Number of Bombs	Number of Aircraft	Accuracy (m, CEP)
World War II	9,070	3,024	1,000
Korea	1,100	550	300
Vietnam	176	44	125

During the Vietnam War, 48% of the Paveway bombs directly hit their target compared to only 5.5% of conventional, unguided bombs[38]. Thus, with the advent of the laser guided bomb, precision guided tactical systems changed the tactics of the U.S. warfighter. Where previously a larger number of larger impact weapons were required to hit their targets due to the inaccuracies involved, now smaller, more precise weapons were able surgically eliminate targets[28].

In addition to the advance in the U.S., during the 1960s and 70s, the Soviet Union continued to invest in increasingly sophisticated precision weapons while simultaneously increasing its fleet strength. These threats led the U.S. to strengthen its countermeasures. Included in this strengthening was the Grumman F-14 Tomcat with its six AIM-54 Phoenix air-to-air missiles[41]. The Phoenix missiles use SAHR from the AWG-9 radar onboard the F-14 for initial and mid-course guidance to the target. Approximately 18 km from the target, the missile uses active radar homing to improve terminal accuracy[41]. The combination of the Phoenix and the AWG-9 radar provided the first air-to-air tactical system capable of tracking multiple targets and missiles simultaneously (allowing up to 24 targets to be tracked with up to six Phoenix missiles in the air) [41]. In addition to the Phoenix air-to-air missile, a new surface to air missile, the Standard Missile (SM-1/SM-2) replaced the Tartar and Terrier SAMs to provide relief from the Soviet threat[42]. These missiles use onboard inertial navigation as well as SAHR from the shipboard Aegis radar during its terminal phase to fly an optimal path to their targets. In addition, mid-course corrections are capable of being commanded[42].

The Gulf War showed the effectiveness of precision guided munitions. Only 4.3% of the total weapons (by tonnage) were laser-guided bombs. However, these weapons caused approximately 75% of the significant damage to Iraqi strategic and operational targets[43]. To further this effectiveness, an effort to convert unguided, conventional bombs to "smart" guided bombs has been underway since 1997. Joint Direct Attack Munition (JDAM) bombs use an integrated inertial guidance system combined with global position system (GPS) data to provide accuracies better than 13 m (CEP)[44]. In a similar manner to how laser guided bombs changed the game in 1970s, JDAMs are revolutionizing the tactical field today.

Another critical, non-weaponized tactical system that has emerged due to the advent of GPS technology is the precision airdrop system[45-47]. This is a vital capability that supports rapid deployment of war fighters and supplies. Using onboard GPS and an inertial navigation system, a guided parafoil system is able to deliver payloads up to 42,000 lbs with sub-100 m miss distances[45]. During Operation Enduring Freedom this technology became the preferred method for daily resupply of U.S. military personnel.

D. Future Tactical Systems

Combining GPS, laser guidance, and inertial navigation systems shows promise to enable longer range flights with higher delivery accuracy of tactical systems[44]. This improvement in navigation may lead to a day in which guidance is not required. The current tactical systems require guidance because the speed of these systems generally do not allow them to reach their targets quick enough to preclude the target from moving out of the way. One solution to this problem would be directed-energy systems (e.g., lasers) with enough power to be tactically effective[28]. These systems would provide speed-of-light transit times to a target, which would neutralize the threat.

IV. Long-Range Systems

A. Intercontinental Ballistic Missiles

1. Early Intercontinental Ballistic Missiles

In 1934, Werner von Braun developed the A-2 which included a gyroscopic stabilizer located near the center of gravity. In 1939, the A-5 was developed that included a three-dimensional gyroscopic control system in which jet rudders and actuators were used for control. To improve upon the A-series designs, one of the first guidance and control simulation laboratories was created in Peenemunde, Germany. Tests facilities such as these enabled the development of the V-1, a winged, subsonic cruise missile controlled by an inertial guidance system, and the V-2 which served as a scaled-up version of the earlier A-series rockets[4,48]. In 1945-46, von Braun and additional German scientists were brought to the U.S. to resume V-2 flight tests at the White Sands Proving Grounds. On 24 February 1949, the unguided, two-stage Bumper-WAC (a U.S. corporal second-stage rocket on a first stage German V-2) was launched to an unprecedented altitude of 250 miles[49]. The improved performance of rockets following World War II enabled the development of intercontinental ballistic missiles (ICBMs); however, such systems would require improved inertial navigation systems and onboard guidance algorithms. In 1951, the U.S. Air Force began development of the first ICBM, the Atlas, which later served as the Mercury launch vehicle[50]. Additionally, the Titan ICBM was developed in 1955 and upgraded to include an inertial guidance system to improve accuracy in 1960 to the Titan II, which later served as the Gemini launch vehicle[51]. The increase in range, time, and accuracy requirements for these flights led to advances in both inertial navigation systems and onboard guidance algorithms.

2. Modern ICBMs

Advancements in inertial navigation and computational resources have culminated in the highly accurate ICBMs of today. These advancements are shown for various ICBMs in Figure 5 and 6. For example, during the first and second stage of flight, the the Missile Guidance Set (MGS) of the Minuteman ICBM controls missile orientation through gimbaling of the nozzles. The onboard computer controls the stage separation as well as subsequent stage ignition. When the onboard computer senses that the missile has reached the correct point in its flight path, thrust termination ports in the third-stage motor are opened for negative thrust. The post-boost vehicle separates from the third stage motor and is maneuvered by the MGS to the predetermined points of reentry vehicle deployment. In this case, advancements in onboard computing enable a highly accurate trajectory to be flown as well as autonomous operation of the vehicle. As such, the guidance system is designed such that it cannot be changed or affected from the ground, a feature which prevents enemy interference with the planned trajectory of the missile[52].

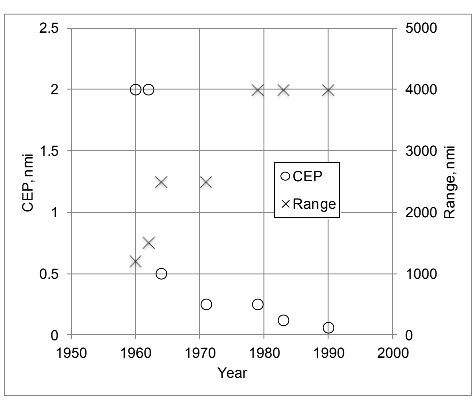

Figure 5. U.S. Navy ICBM accuracy and range compared to year fielded[53].

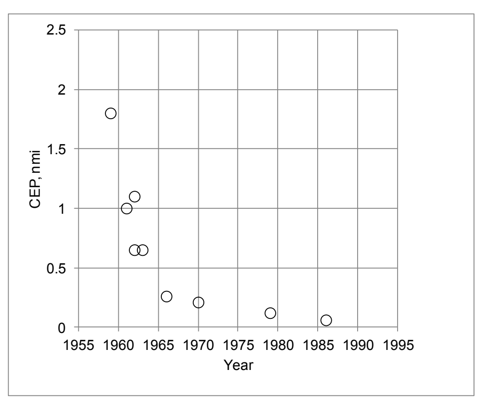

Figure 6. U.S. Air Force ICBM accuracy compared as a function of year fielded[53].

B. Launch Vehicles

Guidance systems for launch vehicles grew out of the development programs for intermediate-range and intercontinental ballistic missiles, as did the vehicles themselves, beginning in the 1950s. However, unlike missiles, the development of onboard inertial guidance systems and vehicles capable of orbit insertion was largely coincident—there was no pre-guidance era for launch vehicles. While there continue to be a mix of stable-platform and strap-down inertial navigation systems, the general historical trend has seen an increase in the use of strap-down systems with the growth of onboard computational power. Early launch vehicles, such as the Atlas-Centaur, utilized stable platforms for their inertial guidance systems, coupled with early digital computers to perform integration and evaluate guidance and navigation equations. Subsequent guidance systems for launch vehicles have achieved significant gains in performance and reliability. As launch system complexity has grown, closed-loop schemes that automatically account for off-nominal and contingency scenarios, such as engine-out, appear attractive. Ascent guidance algorithms have generally increased in complexity and capability as more powerful flight computers have become available, from early radio-guidance systems, to Q-guidance and related schemes, to iterative schemes, such as the Saturn V Iterative Guidance Mode (IGM) and the Space Shuttle Powered Explicit Guidance (PEG). Modern systems continue to utilize open-loop schemes for tower clearance and load management during the initial boost phase, followed by closed-loop ascent guidance to orbit.

1. Early Launch Guidance Systems

Launch vehicle guidance schemes grew directly from technologies developed for missiles, especially intercontinental ballistic missiles (ICBMs) designed to deliver nuclear weapons. The size of rocket required to deliver a nuclear bomb meant ICBMs could be converted to carry payloads to orbit with relatively minor modification. In the United States, the first purpose-built launch vehicle, developed by Project Vanguard in the late 1950s, experienced repeated failures, and was beat to orbit by the Redstone-ballistic-missile-derived Juno I launch vehicle in 1958. The U.S. human spaceflight program also utilized modified missiles for its early flights: the Redstone and Atlas for the Mercury Program and the Titan II for the Gemini Program. The Atlas was used to launch the world's first communication satellite in 1958[54]. Addition of the liquid-fueled Centaur upper stage to the Atlas made Atlas-Centaur into a workhorse launch vehicle whose successor is still in service today[54,55].

Early launch vehicles utilized the same inertial guidance technology (and frequently identical hardware) developed for ICBMs: strap-down inertial platforms with analog control systems[56]. While the earliest guidance schemes used analog control systems, the advent of small digitial computers was roughly coincident with the development of launch vehicles. For example, a digital computer was in use on the Atlas-Centaur guidance system in the early 1960s. Digital computers were generally used with closed-loop guidance schemes.

2. Modern Launch Guidance Schemes

Future launch systems will likely continue to use strap-down inertial navigation systems while improving onboard guidance. Flight performance and efficiency will continue to improve through advanced systems and capabilities, such as look-ahead systems to account for varying atmospheric properties and winds, as well as greater capabilities for managing off-nominal scenarios automatically while maintaining a fuel-optimal flight path. Increasing levels of automation and reliability are also likely, as vehicle designers attempt to increase readiness and reduce operation costs.

New and near-term launch vehicles include the Evolved Expendable Launch Vehicles (EELVs), modern versions of the Atlas and Delta families of rockets, the Falcon family of launch vehicles, and NASA's Space Launch System (SLS). From a guidance system perspective, these vehicles rely heavily on flight-proven algorithms and strategies and have generally pursued incremental improvements. The Falcon vehicles utilize a mix of explicit and perturbation-based guidance algorithms coupled with inertial navigation. While these algorithms are heavily influenced by those flown on other vehicles, the Falcon 9 incorporates a global positioning system sensor to improve the navigation state. While currently single-fault tolerant, the Falcon 9 is designed to be upgradable to human-rated levels of reliability[57,58]. The SLS guidance system is also largely based on heritage systems, especially the Space Shuttle. SLS will utilize a similar ascent guidance scheme, with open-loop boost guidance followed by PEG-derived ascent guidance. SLS guidance design incorporates high reliability and robustness from the outset for human rating. SLS will also fly highly optimized ascent trajectories, requiring the ascent guidance system to cover a large flight envelope, a task for which PEG is well-suited[59].

A major weakness of heritage algorithms and schemes is their dependence on mission-specific constants. For instance, the trajectory and load design process for a given Space Shuttle mission started 303 days prior to launch. While later revisions to this process reduced time to 198 days for standard flights to ISS[60], this remained a major resource commitment and significantly reduced mission flexibility throughout the life of the Space Shuttle program. Future systems could be more adaptable and model-based, reducing operational costs and improving flexibility. Launch vehicle design and development remains difficult with guidance design for such systems typically driven by fuel-optimality concerns due to weight issues. These issues have not gone away, and will continue to present challenges for the forseeable future[61].

C. Notable Long-Range and Launch Guidance Systems

1. Q-Guidance

The Q-Guidance scheme was developed by Richard Battin and Hal Lanning of Draper Laboratory in 1955 (see Ref. 62 for more detail) for the Atlas ICBM, then under development by the U.S. Air Force. However, the Q-Guidance scheme was never used for Atlas. Instead, it flew first on the Thor Intermediate Range Missle and later on the U.S. Navy's submarine-launched Polaris missle. The fundamental relation of the Q-Guidance scheme is given in Eq. (1):

$$\frac{d\mathbf{v}_g}{dt} = -\mathbf{a}_T - \mathbf{Q}\mathbf{v}_g \qquad (1)$$

The primary advantage of the Q-Guidance scheme was that it removed the need to compute gravity in the onboard guidance equations and encapsulated it and other complexities in the Q matrix. The Q matrix, from which the name Q-Guidance is derived, could be computed prior to flight, thus avoiding computational complexity and allowing use of early onboard flight computers. The Q-Guidance scheme later evolved into several algorithms, both for boost and in-space applications[62]. Q-Guidance has remained a topic of study since its inception[63], and continues to form the basis of new guidance schemes[64].

2. The Saturn Family and Iterative Guidance Mode

The Saturn family of launch vehicles was the first U.S. launch vehicles designed from the start with humans in mind. They were designed to accommodate a wide range of payloads and missions and did so during their operational lifetime. Saturn launch vehicles supported the Apollo testing and development program, the Apollo lunar missions, Skylab, and the Apollo-Soyuz Test Project. There were three vehicles in the Saturn family: the Saturn I and IB, which flew a combined 19 flights, and the Saturn V, which flew a total of 13 flights[65]. These rockets were develed in series, with the previous variant generally serving as a stepping stone for later variants. For instance, the second stage of the Saturn IB was nearly identical to the third stage of the Saturn V, including the avionics and guidance system[65]. This strategy provided NASA with additional operational and test experience prior to the Apollo lunar flights.

With human payloads in mind, the Saturn vehicles were designed for maximum reliability. This necessitated the use of a closed-loop guidance scheme which could handle off-nominal scenarios automatically during flight. To provide this capability, the Iterative Guidance Mode, or IGM, was developed. IGM is an explicit scheme that solves the two-point boundary-value problem in a near-optimal sense to target a prescribed radius/velocity/flight-path-angle target relative to the Earth[67]. The iterative portion of the scheme centers upon evaluating the equations of motion onboard during flight. IGM is initiated after the open-loop first stage time-tilt steering program completes (the S-IV stage on the Saturn IB, S-II stage on the Saturn V). IGM was also used for in-space maneuvers on the Saturn V with minor modifications: the radius/velocity/flight-path-angle target was reevaluted at each guidance time step based on the target conic[67]. IGM was run at approximately 1 Hz[65]. The flexible and iterative nature of IGM allowed it to easily compensate for in-flight engine-out scenarios through modification of guidance constants[67].

The Saturn avionics suite included an inertial navigation system, digital computer, and analog flight control system[65,67]. The Saturn IB/V inertial platform was an outgrowth of the system developed for Jupiter missile program and early Saturn I launch vehicles[65]. Reliability was designed into the system, both at the component and the system level. Redundancy was not applied uniformly, but was selectively chosen to achieve the best overall reliability for the cost, mass, and complexity. By this point in time, the digital flight computer system was thought to be much more reliable than electro-mechanical analog systems used in the stable platform and analog flight-control system[68]. The reliability of the Saturn guidance system allowed the Apollo 6 test flight to achieve partial success instead of failure by adjusting the ascent trajectory after two premature first-stage engine shutdowns and the Apollo 12 mission to reach orbit nominally after multiple lightning strikes disabled the Crew Module guidance and control system (these systems were reinitialized in Earth orbit prior to the trans-lunar injection burn)[65].

3. The Space Shuttle and Powered Explicit Guidance

The Space Shuttle was developed in the 1970s and made its first flight on April 12, 1981. The Space Shuttle was only the second launch system designed for human crews and was designed for maximum reliability. The winged orbiter also presented a new ascent guidance challenge: accommodating a wide variety of ascent abort scenarios. The Space Shuttle inertial navigation system consisted of three inertial measurement units. Data from a single IMU was selected by the onboard fault detection system[69]. The Space Shuttle also incorporated significant redundancy in its digital flight computers: four identical, voting computers were used with a fifth, dissimilar, hot-swap capable computer used as backup. During ascent, guidance was open-loop during first stage (flight with the solid rocket boosters), using pregenerated profiles for thrust and attitude based on constraints. The second stage (post solid rocket booster jettison) utilized the closed-loop PEG algorithm (as shown in Figure 7).

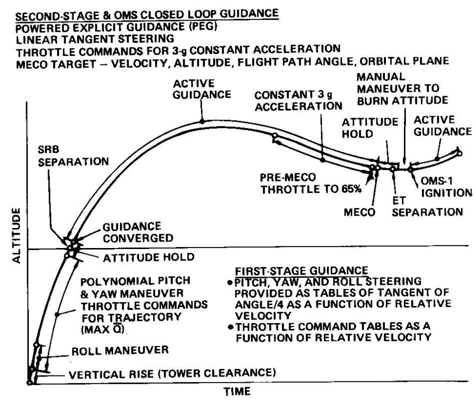

Figure 7. Nominal Space Shuttle ascent guidance sequence[71].

The Powered Explicit Guidance (PEG) algorithm was developed for the Space Shuttle, and was used in several forms as the guidance algorithm for all powered flight scenarios[69]. PEG was developed from the Linear Tangent Guidance (LTG)[71]. LTG was a simplified vector form of the linear-tangent steering law from Apollo and was developed by Roland F. Jaggers, who worked on Saturn's IGM[67,69,72]. PEG is an iterative predictor-corrector that is used to generate steering commands to a desired target. It was typically run at about 0.5 Hz and required three to four iterations to converge to an initial solution once activated[68]. The flexibiliy of PEG allowed it to accommodate a wide variety of maneuvers and targets. PEG was able to provide coverage for all required Space Shuttle maneuvers, including second stage ascent, deorbit, and all abort scenarios, including return to launch site (RTLS), transoceanic abort landing (TAL), abort once around (AOA), and abort to orbit (ATO) [69].

V. Entry Systems

A. Hypersonic Guidance

Hypersonic entry is generally unpowered; steering is accomplished via changes in aerodynamic forces and moments. To date, hypersonic entry guidance systems have been designed to achieve a set of target conditions at parachute deployment (or another vehicle transition) by modulating the bank angle and, in some cases, the angle-of-attack of the vehicle. For a majority of entry systems, a fixed center-of-mass offset is utilized to set the angle of attack and reaction control system commands are utilized to adjust bank angle throughout the trajectory. In this manner, the vehicle can adjust its energy depletion rate based on onboard navigation data. Hypersonic aeromaneuvering via bank angle modulation is shown in Figure 8, where ϕ is the bank angle.

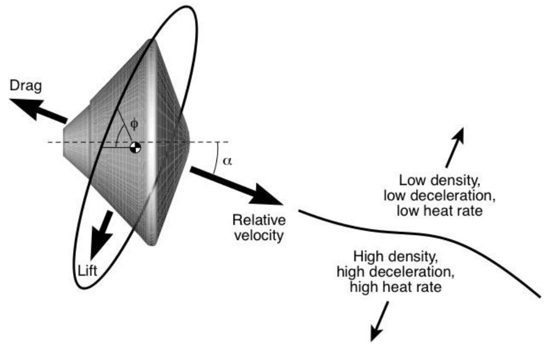

Figure 8. Bank angle modulation.

While the United States' first human entry vehicle, Mercury, was unguided, all subsequent crewed vehicles have included hypersonic entry guidance. Two different hypersonic entry guidance schemes were developed for Project Gemini. The first algorithm computed a constant bank angle to follow an *a priori* computed trajectory. The second guidance algorithm predicted the lift to required to null the predicted terminal error as soon as possible; once errors were nulled within a given tolerance, a ballistic trajectory was flown[73-75]. Flight experience with the first of these two algorithms showed significant sensitivity to the estimation of day-of-flight lift-to-drag ratio (which was highly uncertain). As a result, this algorithm was only flown on three of the Gemini missions (Gemini V, VI-A, and VII) [73].

The Apollo entry guidance algorithm was designed to accommodate the high-energy entries associated with return from the Moon. This required the inclusion of the capability to peform a skip entry, i.e., an exoatmospheric trajectory segment after initial entry. The guidance algorithm was divided into five phases as shown in Figure 9.[9,76,77] The first of these phases ensured that the vehicle did not skip out of the atmosphere while maintaining sufficient energy to permit the vehicle to reach the landing point. The second phase was used to predict the range to the landing site based on a constant lift-to-drag ratio. If the predicted range exceeded the desired range, a constant drag trajectory was commanded until the predicted range error was less than 25 nmi. The third phase followed a reference trajectory to steer the vehicle to the desired atmospheric exit condition. During Phase 4, no range control was provided due to low dynamic pressure. In this phase, the trajectory was assumed to be Keplerian. The fifth and final phase was a terminal point controller. Here, a pre-generated reference trajectory was used to generate steering commands to null the terminal range error. During entry, crossrange error was managed independently by changing the sign of the bank angle using deadbands according to the deviation from the target.

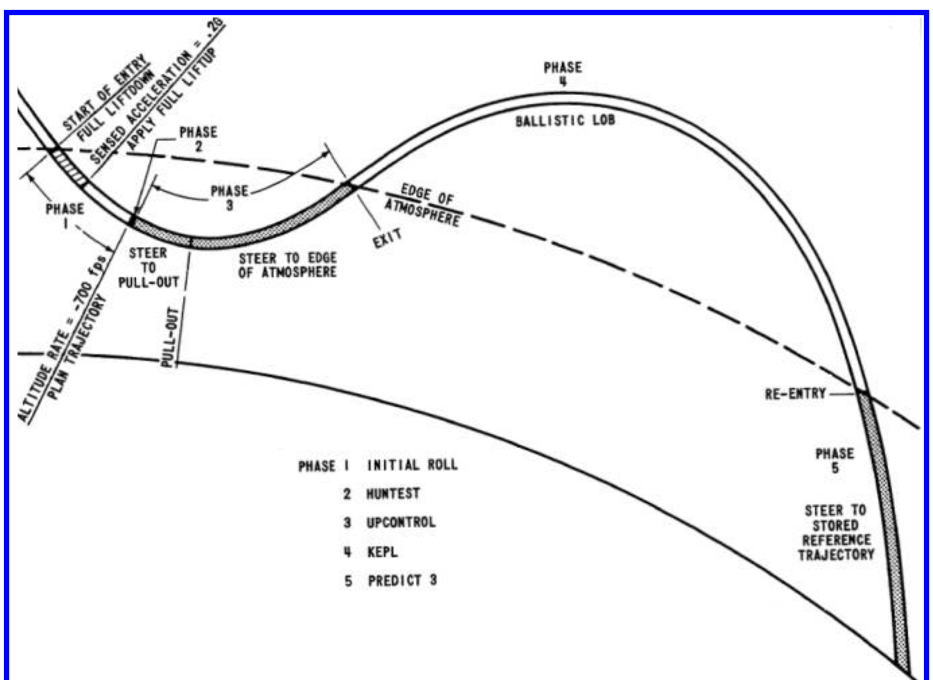

Figure 9. Apollo entry guidance phases[76].

The Space Shuttle, developed in the 1970s, utlized both bank angle and angle-of-attack control during entry. Like the Apollo entry guidance algorithm, the Shuttle entry guidance scheme consisted of multiple phases, each of which prescribed a drag profile as a function of velocity or energy[10]. A reference trajectory was generated on the ground prior to entry. The commanded lift-to-drag ratio (L/D) was then determined using a proportional-integral-derivative control structure with the stored reference:

$$\left(\frac{L}{D}\right)_C = \left(\frac{L}{D}\right)_0 + f_1\left(D - D_0\right) + f_2(\dot{h} - \dot{h}_0) + f_4\int(D - D_0)dV \qquad (2)$$

Each of the Space Shuttle entry phases is shown in Figure 10.

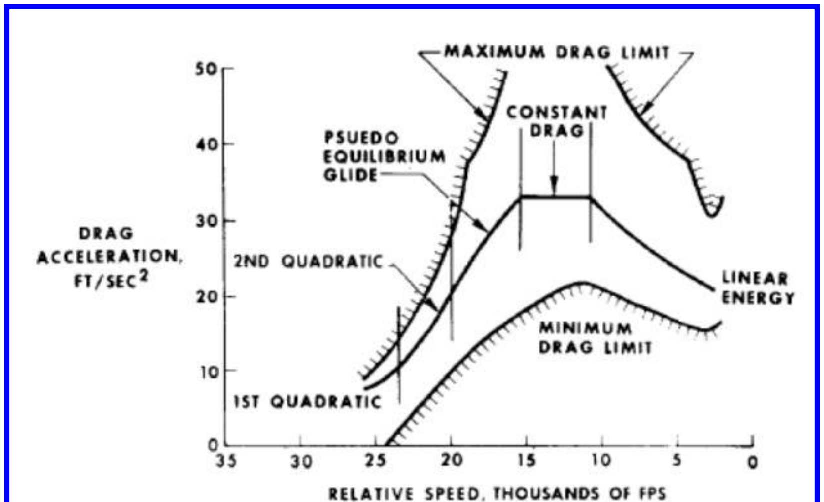

Figure 10. Space Shuttle entry guidance phases[10].

The first phase of the Space Shuttle entry guidance was the Temperature Control phase, where a quadratic relationship beween drag and velocity was defined and followed. The second phase continued temperature control with a different quadratic relationship between drag and velocity. During the third phase, Equilibrium Glide, it was assumed that the flight-path angle was small and remained nearly constant, allowing an analytic relationship for the prescribed drag as a function of velocity to be used. During the fourth phase, constant drag was used to limit peak deceleration. Finally, during the fifth phase a Linear Energy Transition is prescribed to guide the vehicle to the Terminal Area Energy Management conditions. This transition was managed with a linear relationship in terms of energy because the small flight-path-angle assumption of equilibrium glide was violated in this flight regime. Angle-of-attack control was used throughout entry to track a prescribed profile consistent with the pre-generated drag profiles used for range control.[10]

Project Orion will utilize the PredGuid entry guidance algorithm.[80,81] PredGuid utilizes portions of the Apollo guidance algorithm and the PRED GUID aerocapture numeric predictor-corrector algorithm[82] to improve accuracy during skip entries. The numeric predictor-corrector replaces most of the second, third, and fourth phases of the Apollo algorithm with improved performance and flight envelope coverage.[83]

Until recently, no vehicle has flown hypersonic entry guidance on Mars. This changed with the arrival of the Mars Science Laboratory (MSL) on August 6, 2012. MSL used a modified version of Apollo's final phase algorithm[11,78]. This algorithm was selected for its simplicity and accuracy. For Mars, a new heading alignment phase was appeneded to the Apollo final phase algorithm to maintain altitude prior to landing in the thin Mars atmosphere. MSL achieved range control by predicting the downrange flown and commanding a bank angle to correct for range errors. In addition, crossrange errors were controlled using a deadband scheme. By incorporating hypersonic guidance, MSL was able to greatly reduce its landed footprint, relative to past unguided Mars missions in which the focus had been improvements in approach navigation only. This resulted in a 3-σ landed footprint below 20 km, enabling landing within Gale Crater (see Figure 11).

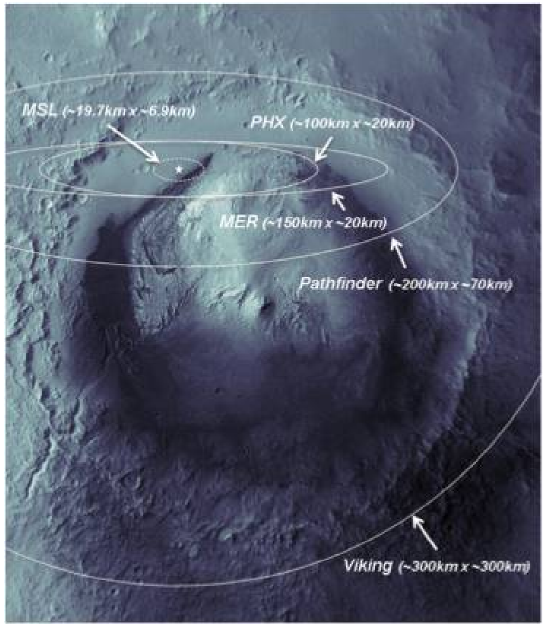

Figure 11. Mars Science Laboratory landed footprint at Gale Crater relative to past unguided mission performance

The Mars 2020 mission, presently in development, plans to fly a hypersonic guided entry trajectory similar to MSL augmented by a potential change in the trigger than enables parachute deployment to reduce range to the target, enabling a smaller landed footprint and more diverse science targets.[84]

B. Propulsive Guidance

Unlike hypersonic entry guidance which leverages aerodynamic forces to shape the trajectory, propulsive guidance relies on thrust to alter the trajectory. The first U.S. propulsive soft-landing guidance algorithm used on another planterary body was developed as part of the Lunar Surveyor[85] program. Slight variations of this algorithm, commonly referred to as a gravity turn, were also implemented in several other missions including Viking and Phoenix[85,86]. This guidance law is straightforward to implement and test in flight software, resulting in reliable operations.

Gravity turn guidance is characterized by orienting thrust opposite the velocity direction and has the desirable property that as the velocity approaches zero, the flight path angle tends towards the vertical. This is a near-propellant optimal algorithm in which the thrust magnitude is prescribed as a function of the slant range to the target.

$$T = m\left(g + \frac{v^2}{2R}\right) \tag{3}$$

This guidance law results in constant acceleration during terminal descent. Due to numerical sensitivities as the slant range tends to zero, this guidance law is generally terminated at a near-surface target elevation and a separate vertical descent phase is incorporated to approach the surface at near constant velocity.

The Apollo Lunar Module also used a propulsive terminal descent algorithm[87]. Figure 12 shows the three phases of this algorithm. The Braking Phase was initiated manually by the Lunar Module Pilot approximately 10 minutes prior to propulsive descent initation (PDI). The exact time of PDI is computed using a near-optimal polynomial equation for the commanded acceleration that targets a landing site approximately 4.5 km short of the actual target. A similar routine was used during the Approach Phase; however, now the target is reset to the desired landing site. This landing site redesignation was performed in order to account for the roation of Lunar surface. The Terminal Descent phase begins approximately 30 m above the surface and approximately 11 m downrange from the target. This phase nulls the forward and lateral velocity to produce a vertical approach to the Lunar surface.

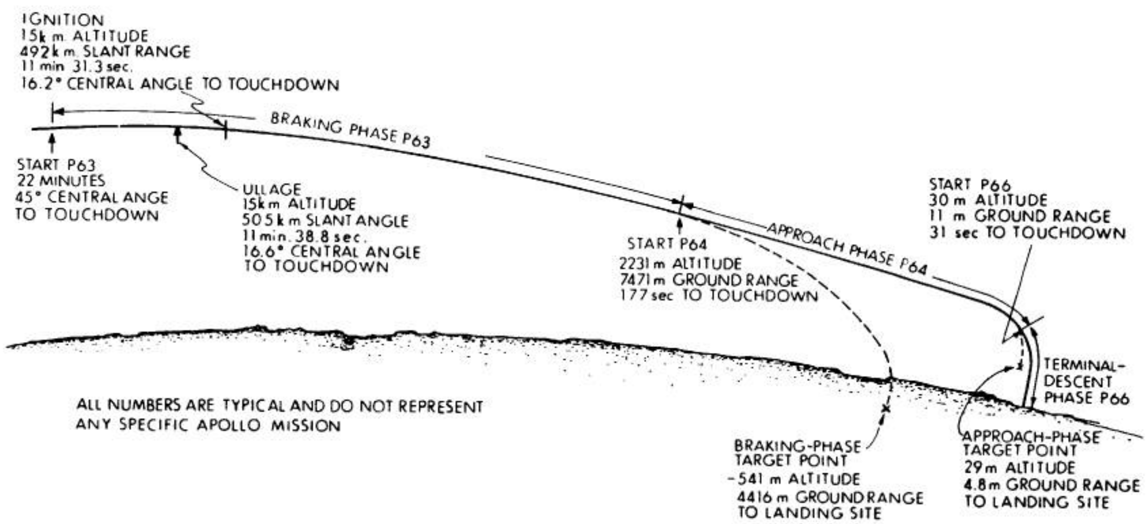

Figure 12. Apollo Lunar Module guidance phases[87].

Other robotic exploration missions have used propulsive terminal descent algorithms. For example, Mars Pathfinder (MPF) used a straightforward algorithm to process radar measurements and predict the appropriate altitude at which to fire its retrorockets in order to achieve a desired terminal velocity[88]. A similar system was implemented for the Mars Exploration Rovers (MER). However, in addition to the vertical descent rockets found on MPF, MER incorporated transverse rockets the Transverse Impulse Rocket Subsystem (TIRS) with a descent imaging system to measure and correct for any excess horizontal velocity[89]. The TIRS system can be viewed as the first straightforward step towards more complex terrain-relative navigation systems.

The Mars Science Laboratory used a four phase propulsive descent and landing strategy. During the approach phase, a polynomial guidance algorithm was used, similar to that of Apollo. This was followed by a constant velocity phase where the descent stage speed was maintained. Subsequent to this, a constant deceleration phase was executed, followed by a throttle down where four of the engines were reduced to 1% throttle[90]. The Mars 2020 mission is planning a similar descent and landing architecture with potential augmentations that may include terrain-relative navigation and hazard detection and avoidance technologies.

VI. Conclusions

A survey of previous short-range, long-range, and entry guidance systems was provided for civilian and military applications. In each of these applications, accuracy has improved with time, an advance generally attributed to the transition from passive and open-loop guidance systems to active, closed-loop guidance sytems. This paradigm shift was enabled by the development of onboard inertial navigation systems, which in turn, were enabled by miniaturized sensors and computing hardware. Continuous improvement, affordability and maintainability concerns, have further shifting inertial guidance systems to strapdown architectures for aerospace systems. Operational reliability of inertial guidance systems has continued to improve; however, redundancy remains common due to the criticality of onboard guidance systems. Future aerospace applications will likely require more complex guidance algorithms that leverage the computing power of modern flight computers and incorporate new navigation sensor technologies. Aerospace systems leveraging microelectromechanical technology will become more common as the this field matures, continuing the historical trend of increasing capability and autonomy.

Appendix A: Guidance System Applications in Aerospace

	System	Year	Active or Passive	Closed-Loop or Open-Loop	Predictive or Reference Path	Inertial Navigation System
Short-Range Systems	Kettering Aerial Torpedo "Bug"	1918	Passive	Open-Loop	-	No
	Robin Bomb	1942	Passive	Open-Loop	-	No
	Pelican Bomb	1942	Active	Open-Loop	-	No
	G7e/T4 Falke	1943	Passive	Open-Loop	-	No
	G7es/T5 Wren	1943	Passive	Open-Loop	-	No
	Mark-24 Torpedo	1943	Passive	Open-Loop	-	No
	AZON Bomb	1944	Passive	Open-Loop	-	No
	V-2 Rocket	1944	Active	Open-Loop	-	Yes
	BAT Bomb	1945	Active	Closed-Loop	-	No
	Tarzon Bomb	1949	Passive	Open-Loop	-	No
	Razon Bomb	1950	Passive	Open-Loop	-	No
	Terrier Missile	1953	Semi-Active	Open-Loop	-	No
	Falcon Bomb	1956	Semi-Active	Open-Loop	-	No
	Talos Missile	1958	Semi-Active	Open-Loop	-	No
	Tartar Missile	1962	Semi-Active	Open-Loop	-	No
	Paveway Bomb	1964	Passive	Open-Loop	-	No
	Phoenix Missile	1974	Passive/ Active	Closed-Loop	Predictive	No
	SM-1 Standard Missile	1970	Semi-Active	Closed-Loop	Predictive	Yes
	SM-2 Standard Missile	1981	Semi-Active	Closed-Loop	Predictive	Yes
	JDAM Bomb	1997	Active	Closed-Loop	Predictive	Yes
	Precision Air Drop	2008	Active	Closed-Loop	Predictive	Yes
Long-Range Systems	A-2	1934	Active	Open-Loop	-	No
	A-5	1939	Active	Open-Loop	-	No
	V-1 Bomb	1944	Active	Closed-Loop	-	No
	Bumber-WAC	1949	Active	Open-Loop	-	Yes
	Atlas	1951	Passive	Open-Loop	-	No
	Titan 1st Stage	1958	Active	Open-Loop	-	Yes
	Titan 2nd Stage	1958	Active	Closed-Loop	Predictive	Yes
	Delta 1st Stage	1960	Active	Open-Loop	-	Yes
	Delta 2nd Stage	1960	Active	Closed-Loop	Predictive	Yes
	Saturn 1st Stage	1961	Active	Open-Loop	-	Yes
	Saturn 2nd Stage	1961	Active	Closed-Loop	Predictive	Yes
	Saturn 3rd Stage	1961	Active	Closed-Loop	Predictive	Yes
	Minuteman	1962	Active	Closed-Loop	Predictive	Yes
	Space Shuttle 1st Stage	1981	Active	Open-Loop	Predictive	Yes
	Space Shuttle 1st Stage	1981	Active	Closed-Loop	Predictive	Yes
	Falcon 1st Stage	2006	Active	Open-Loop	-	Yes
	Falcon 2nd Stage	2006	Active	Closed-Loop	Predictive	Yes
ms	Lunar Surveyor	1962	Active	Closed-Loop	Predictive	Yes
	Gemini	1962	Active	Closed-Loop	Reference Path	Yes
	Apollo Command Module	1968	Active	Closed-Loop	Reference Path	Yes

	Apollo Lunar Module	1969	Active	Closed-Loop	Predictive	Yes
	Viking	1976	Active	Closed-Loop	Predictive	Yes
	Space Shuttle	1981	Active	Closed-Loop	Reference Path	Yes
	Mars Pathfinder	1997	Active	Open-Loop	-	Yes
	Mars Exploration Rovers	2004	Active	Open-Loop	-	Yes
	Phoenix	2008	Active	Closed-Loop	Predictive	Yes
	MSL Entry	2012	Active	Closed-Loop	Reference Path	Yes
	MSL Terminal Descent	2012	Active	Closed-Loop	Predictive	Yes

References

1. Yanushevsky, R., Modern Missile Guidance, Boca Raton, FL, CRC Press, 2008.
2. Partington, J. R., "A History of Greek Fire and Gunpowder," *Miscellaneous Treatises on Military Arts*, The Johns Hopkins University Press, Maryland, 1999, pp. 148-154.
3. Glick, T., Livesey, S. J., and Wallis, F., "Medieval Science, Technology, and Medicine: An Encyclopedia," *Artillery and Firearms*, Taylor and Francis Group, New York, 2005, pp. 54-55.
4. Spearman, M. L., "Historical Development of Worldwide Guided Missiles," AIAA 1978-210, *AIAA 16th Aerospace Sciences Meeting*, 16-18 Jan. 1978, Huntsville, AL.
5. Angelo, Jr., J. A., "Frontiers in Space: Rockets," *From Fire Arrows to Mars Missions*, Infobase Publishing, New York, 2006, pp. 1-8.
6. Darling, D., "The Complete Book of Spaceflight: From Apollo 1 to Zero Gravity," *Kettering Bug*, John Wiley and Sons, Inc., New Jersey, 2003, pp. 221.
7. SP-4206
8. Goodstein, R., "Guidance law applicability for missile closing," Guidance and Control of Tactical Missiles, AGARD Lecture Series, no. 52, May 1972.
   Bishop
9. Morth, R."Reentry Guidance for Apollo," Massachusetts Inst. Of Technology Instrumentation Lab., Rept. R-532, Vols. 1-2, Cambridge, MA, Jan. 1966.
10. Harpold, J. C. and Graves, C. A., "Shuttle Entry Guidance," Tech. Rep. *NASA-TM*-79949, NASA, Houston, Texas, Feb. 1979.
11. Carman, G. L., Ives, D. G., and Geller, D. K., "Apollo-Derived Mars Precision Lander Guidance," AIAA Paper 98-4570, Aug. 1998.
12. Duncan, R. C. and Gunnersen, Jr., A. S., "Inertial Guidance, Navigation, and Control Systems," *Journal of Spacecraft and Rockets*, Vol. 1, No. 6, 1964.
13. Pasik, D. J., Gneses, M. I., and Taylor, G. R., "A Ring Laser Gyro Strapdown Inertial Navigation System: Performance Analysis and Test Results," AIAA 75-1095, *AIAA Guidance and Control Conference*, 20-22 Aug. 1975, Boston, MA.
14. Gautraud, J. A. and Elvey, L. E., "Tactical Missile Inertial Reference Platforms," AIAA 79-1941, *AIAA 2nd Computers in Aerospace Conference*, 1979, Los Angeles, CA.
15. Lee, B., "Integrated Inertial Reference – Inertial Navigation System," *Journal of Aircraft*, Vol. 13, No. 7, 1976.
16. Rounds, S. F. and Marmar, G., "Stellar-Inertial Guidance Capabilities for Advanced ICBM," AIAA 83-2297, *AIAA Guidance and Control Conference*, 1983, Gatlinburg, TN.
17. Andre, M. H. and Czaja, J. J., "Minuteman Inertial Guidance Assessment: The Next Best Thing to Flight Tests," *Journal of Guidance, Control, and Dynamics*, Vol. 6, No. 3, 1983, pp. 156-161.
18. Reams, G. A., Roberts, G. E., and Fulcher, W. E., "Effects of Polar Motion on ICBM Accuracy," AIAA 83-2295, *AIAA Guidance and Control Conference*, 1983, Gatlinburg, TN.
19. Ford, C. T., "Gravitational Model Effects on ICBM Accuracy," AIAA 83-2296, *AIAA Guidance and Control Conference*, 1983, Gatlinburg, TN.
20. Nosek, Thomas P., "Space Shuttle as a Dynamic Test Tool for Missile Guidance Systems," *Journal of Guidance*, Vol. 6, No. 6, 1983, pp. 530-531.
21. Merhav, S. J., "A Nongyroscopic Inertial Measurement Unit," *Journal of Guidance*, Vol. 5, No. 3, pp. 227-235.
22. Chen, J., Lee, S., and DeBra, D. B., "Gyroscope Free Strapdown Inertial Measurement Unit by Six Linear Accelerometers," *Journal of Guidance, Control, and Dynamics*, Vol. 17, No. 2, pp. 286-290.
23. Nowarra, H.J., *German Guided Missiles, Schiffer Military/Aviation History*, Atglen, PA, 1993
24. Smith, J.F. and Kay, A.L., *German Aircraft of the Second World War*, Nautical & Aviation Publishing Company, Baltimore, MD, 1989, pp. 696-699.
25. Pocock, R.F., *German Guided Missiles of the Second World War*, Arco Publishing Co., Inc., New York, 1967.
26. Werrell, K. P., *The Evolution of the Cruise Missile*, Air University Press, Maxwell AFB, AL, 1985.

27. Trimble, W.F., *Wings for the Navy: A History of the Naval Aircraft Factory*, 1917-1956, Naval Institute Press, Annapolis, 1990.
28. Watts, B.D., “Six Decades of Guided Munitions and Battle Networks: Progress and Prospects,” Center for Strategic and Budgetary Assessments, March 2007.
29. Kopp, C., “Military Technology: Evolution of Guided Torpedoes,” Defense Today, Dec 2010.
30. Milford, F.J., “U.S. Navy Torpedoes: WWII Development of Homing Topedoes 1940-1946,” The Submarine Review, April 1997, pp.75.
31. Mets, D.R., “The Force in US Air Force,” *Aerospace Power Journal*, Fall 2000, pp. 61-62.
32. Campbell, J., “Naval Weapons of World War Two,” *Guided Missiles*, Anova Books Company Ltd., London, 1985, p. 171.
33. http://en.wikipedia.org/wiki/File:BAT-PB4Y-wingbat.jpg
34. Kopp, C., “Active and Semiactive Radar Missile Guidance,” Australian Aviation, June 1982.
35. “Introduction to rocket and guided missile fire control,” *Fire Control Fundamentals*, NAVPERS 91900, 1953
36. Olds, R., *Fighter Pilot: The Memoirs of Legendary Ace Robin Olds*, St. Martin’s Press, 2010.
37. Schmitt, V. R., *Controlled Bombs and Guided Missiles of the World War II and Cold War Eras: An Inside Story of Research and Development Programs*, Society of Automotive Engineers, Warrendale, PA, 2002.
38. Hallion, R.P., “Precision Guided Munitions and the New Era of Warfare,” APSC Paper Number 53, June, 1996.
39. Tilford, E.H., *Setup: What the Air Force Did in Vietnam and Why*, Air University Press, Alabama, 1991.
40. Clancy, T., *Fighter Wing,* Harper Collins, London, 1995.
41. Chant, C., *World Encyclopedia of Modern Air Weapons*, Patrick Stephens Ltd, 1998.
42. Korb, E.L. (ed.), *The World’s Missile Systems*, General Dynamics, Pomona, 1988.
43. Cohen, E. (ed.), *Gulf War Air Power Survey, Volume IV: Weapons, Tactics, and Training and Space Operations*, Department of the Air Force, Jan. 1994.
44. Davis, C.H., “JDAM: The Kosovo Experience and DPAS,” The Boeing Company, April 2000.
45. Hattis, P.D., Appleby, B.D., and Fill, T.J., “Precision Guided Airdop System Flight Test Results,” AIAA-97-1468, 1997.
46. Carter, D., George, S., Hattis, P., Singh, L. and Tavan, S., “Autonomous Guidance, Navigation, and Control of Large Parafoils,” AIAA 2005-1643, May 2005.
47. Carter, D.W., George, S., Hattis, P.D., McConley, M.W., Rasmussen, S.A., Singh, L., and Tavan, S., “Autonomous Large Parafoil Guidance, Navigation, and Control System Design Status,” AIAA 2007-2514, May 2007.
48. Spangenburg, R. and Moser, D. K., “Wernher von Braun: Rocket Visionary,” *Chronology*, Revised Edition, Infobase Publishing, New York, 2008, pp. 141-144.
49. Norrell, D. M., Browning, C. R., and Burns, K., “Operation Sandy,” AIAA 2006-59451, *Space 2006*, 19-21 September 2006, San Jose, CA.
50. Neufeld, J., “The Development of Ballistic Missiles in the United States Air Force,” *A Radical Reorganization*, Office of Air Force History, United States Air Force, Washington, D.C., 1990, pp. 93-118.
51. Frew, J. J. and Currier, I. S., “Titan Launch Vehicle Program Overview,” AIAA 1997-2988, *AIAA 33rd Joint Propulsion Conference and Exhibit*, 1997, Seattle, WA.
52. Larsen, S. B., “History of Minuteman System Update,” AIAA 1997-3396, *AIAA 33rd Joint Propulsion Conference and Exhibit*, 1997, Seattle, WA.
53. MacKenzie, D., "Inventing Accuracy," MIT Press, Cambridge, MA, 1990.
54. Patzer, M. And White, R. C., “The Commercial Atlas Today,” AIAA Paper 1990-2715.
55. Greenstein, J. L., “Postflight Guidance Accuracy Analysis of Atlas/Centaur/Surveyor Flights,” *Journal of Spacecraft and Rockets*, Vol. 6, No. 9, September 1969, pp. 971-977.
56. Ordway, F. I., Dahm, W. K., Dannenberg, K., Haeussermann, W., Reisig G., Stuhlinger, E., von Tiesenhausen, G., and Willhite, I., “From Peenemünde, Germany, to Fort Bliss, Texas, White Sands, New Mexico, and Huntsville, Alabama, U. S. A.: A Classic Case Of Technology Transfer Rocket Propulsion, Missile and Launch Vehicle Technology,” International Astronautical Congress Paper IAC-03-IAA.2.4.a.06, September 2003.
57. Space Exploration Technologies, “Falcon 1 Launch Vehicle Payload User’s Guide,” D000973 Rev. 7, Hawthorne, CA, 2008.
58. Space Exploration Technologies, “Falcon 9 Launch Vehicle Payload User’s Guide,” SCM 2008-010 Rev. 1, Hawthorne, CA, 2009.
59. Orr, J. S., “Space Launch System Flight Control,” October 2012, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20130000629_2012018865.pdf, Accessed 27 July 2013.
60. Picka, B. A. and Glenn, C. B. “Space Shuttle Ascent Flight Design Process Evolution and Lessons Learned,” AIAA Paper 2011-7243, September 2011.
61. Ryan, R. S. and Townsend, J. S., “Fundamentals and Issues in Launch Vehicle Design,” *Journal of Spacecraft and Rockets*, Vol. 34, No. 2, March-April 1997, pp. 192-198.
62. Battin, R. H., “Space Guidance Evolution—A Personal Narrative,” *Journal of Guidance and Control*, Vol. 5, March-April 1982, pp. 97-110.
63. Martin, F. H., “Closed-loop Near-Optimum Steering for a Class of Space Missions,” Doctor of Science Thesis, Massachusetts Institute of Technology, Cambridge, MA, May 1965.
64. Bhat, M. S. and Shrivastava, S. K., “An Optimal Q-Guidance Scheme for Satellite Launch Vehicles,” *Journal of Guidance, Control, and Dynamics*, Vol. 10, No. 1, Jan.-Feb. 1987, pp. 53-60.

65. Lucas, W. R., “Saturn Launch Vehicles,” AIAA Paper 81-0900, May 1981.
66. Rudolph, A., “Operational Experience with the Saturn V,” AIAA Paper 68-1003, October 1968.
67. Martin, D. T., Sievers, R. F., O’Brien, R. M., and Rice, A. F., “Saturn V Guidance, Navigation, and Targeting,” *Journal of Spacecraft and Rockets*, Vol. 4, No. 7, July 1967, pp. 891-898.
68. White, J. B., and Moore, F. B., “Application of Redundancy in the Saturn V Guidance and Control System,” AIAA Paper 67-553, August 1967.
69. McHenry, R. L., Brand, T. J., Long, A. D., Cockrell, B. F., and Thibodeau, J. R., “Space Shuttle Ascent Guidance, Navigation, and Control,” *Journal of the Astronautical Sciences*, Vol. 27, Jan.-Mar. 1979, pp. 1-38.
70. Schleich, W. T., “The Space Shuttle Ascent Guidance and Control,” AIAA Paper 1982-1497, August 1982.
71. Jaggers, R. F., “An Explicit Solution to the Exoatmopheric Powered Flight Guidance and Trajectory Optimization Problem for Rocket Propelled Vehicles,” AIAA Paper 1977-1051, August 1977.
72. Rose, M. B. And Geller, D. K., “Linear Covariance Techniques for Powered Ascent,” AIAA Paper 2010-8175, August 2010.
73. Bryson, A. E (ed.), “Guidance and Navigation for Entry Vehicles,” NASA-SP-8015, NASA, Nov. 1968.
74. Harpold, J., “Results of the Reentry Guidance System Used During Project Gemini,” Reentry Guidance and Control Meeting, Ames Research Center, Oct. 1966.
75. Box, D.M., Harpold, J.C., Paddock, S.G., Armstrong, N.A., and Hamby, W.H., “Controlled Reentry,” Gemini Summary Conference Proceedings, NASA SP-138, 1967.
76. Bogner, I., “Description of Apollo Entry Guidance,” NASA CR-110924, Aug. 1966.
77. Moseley, P. E.; Morris, R. L., "The Apollo Entry Guidance: A Review of the Mathematical Development and its Operational Characteristics," Task MSC/TRW A-220, Dec. 1969.
78. Mendeck, G.F. and Craig, L.E., “Entry Guidance for the 2011 Mars Science Laboratory Mission,” AIAA-2011-6639, Portland, OR, Aug. 2011.
79. Cheng, R.K., “Surveyor Terminal Guidance,” NASA CR-57550, 1966.
80. Bairstow, S.H. and Barton, G. H., "Orion Reentry Guidance with Extended Range Capability Using PredGuid," AIAA Paper 2007-6427, August 2007.
81. Putnam, Z.R., Neave, M.D., and Barton, G.H., “PredGuid Entry Guidance for Orion Return from Low Earth Orbit,” 2010 IEEE Aerospace Conference, Big Sky, MT, March 2010.
82. Gamble, J.D., Cerimele, C.J., Moore, T.E., and Higgins, J., “Atmospheric Guidance Concepts for an Aeroassist Flight Experiment,” *Journal of the Astronautical Sciences*, Vol. 36, 1988, pp. 45-71.
83. Putnam, Z.R., Braun, R.D., Bairstow, S.H., Barton, G.H., “Improving Lunar Return Entry Range Capability Using Enhanced Skip Trajectory Guidance,” *Journal of Spacecraft and Rockets*, Vol. 45, No. 2, pp 309-315, March-April 2008.
84. Way, D., "On the Use of a Range Trigger for the Mars Science Laboratory Entry, Descent, and Landing," 2011 IEEE Aerospace Conference, Big Sky, MT, March 2011.
85. Ingoldby, R.N., “Guidance and Control System Design of the Viking Planetary Lander,” Journal of Guidance, Control, and Dynamics, Vol. 1., No. 3, pp. 189-196, May-Jun. 1978.
86. Prince, J.L. Desai, P. N., Queen, E.M., and Grover, M.R., “Mars Phoenix Entry Descent, and Landing Simulation Design and Modeling Analysis,” Journal of Spacecraft and Rockets, Vol. 48, No. 5, pp. 756-764, Sept-Oct 2011.
87. Klumpp, A.R., “Apollo Lunar-Descent Guidance,” R-695, MIT Charles Stark Draper Laboratory, Jun. 1971.
88. Braun, R.D., Spencer, D.A., Kallemeyn, P.H., and Vaughan, R.M., “Mars Pathfinder Entry Navigation Operations,” Journal of Spacecraft and Rockets, Vol. 36, No. 3, pp. 348-356, May 1999.
89. Yang, C., Johnson, A., and Matthies, L., “MER-DIMES: A Planetary Landing Application of Computer Vision,” IEEE Computer Society Internatinoal Confernece on Computer Vision and Pattern Recognition, San Diego, CA., Jun. 2005.
90. San Martin, A. M., Wong, E.C., and Lee, S.W., “The Development of the MSL Guidance, Navigation, and Control System for Entry, Descent, and Landing,” AAS Guidance and Control Conference, Breckenridge, CO., Feb. 2013.