JOURNAL OF GUIDANCE, CONTROL, AND DYNAMICS
Vol. 19, No. 1, January–February 1996

History of Key Technologies

Guidance, Navigation, and Control from Instrumentation to Information Management

Eli Gai
Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts 02139-3563

I. Classical Guidance, Navigation, and Control Systems

THE classical guidance, navigation, and control (GN&C) system, shown in Fig. 1, is a feedback system that includes three subsystems. These subsystems are defined as follows. Navigation is the determination of the position and velocity vectors of a moving platform in a specified coordinate frame. Guidance is the determination of a trajectory from a current position and velocity to a desired position and velocity, satisfying specified costs and constraints. Control is the determination of the commands to the vehicle actuators to implement the trajectory, preserving a stable feedback loop.

II. Early Implementations: Mechanical Instrumentation

Any feedback system implementation requires the ability to observe the state of the system, which is implemented by sensors. In a GN&C system, these measurements are provided by the navigation function. The need for accurate navigation appeared in the eighteenth century as a result of lengthy sea travel. The need was to determine a ship's position accurately after being at sea for several weeks. The solutions were based on astronomical measurements, namely, the use of stars. Whereas latitude can be found by measuring the line of sight to the Pole star, however, the determination of longitude requires the knowledge of the elapsed time from leaving home port. More specifically, if you want to know your longitude after 6 weeks at sea to an accuracy of 15 n mile, you need a clock with accuracy of about 1 s/day. In 1714, the British government offered £20,000 ($13 million in today's money) to anyone who could find the longitude to within 30 n mile after 6 weeks. The winner, John Harrison, spent 50 years of his life building a series of mechanical chronometers. In 1773, he won the award.[1] One of his clocks is shown in Fig. 2.

Harrison solved the problem of precise navigation at sea. Navigation issues resurfaced, however, when people started to fly. Aircraft navigation was particularly difficult when you had to fly over water or in bad weather and could not use ground landmarks. Early in the 1930s, the Army Air Corps started to train its flyers to use onboard instrumentation to deduce their position. The idea was to start with the knowledge of your initial position, add to the airspeed the wind speed and direction thus figuring ground speed, then multiply by elapsed time to get the current position. The method was called deduced reckoning, which subsequently was abbreviated to ded and, finally, to dead reckoning by which it is known today.[2]

The importance of the dead reckoning idea was that it lead to the black box concept in which a black box was conceived to do the required computations and provide the pilot with accurate results. The implementation of this concept was done by inertial navigation. In inertial navigation, the computations are based on knowledge of the initial conditions, the gravitational field, and the use of inertial sensors and a clock. A stable platform is isolated from all angular motions using gyroscopes that measure angular rates, torque motors, and gimbals. Accelerometers are mounted on the stable platform, and their outputs are doubly integrated to get position and velocity. A conceptual implementation of an inertial navigation system in which all measurements are mechanically instrumented[3] is shown in Fig. 3. One of the first inertial systems, which was built (by the Massachusetts Institute of Technology Instrumentation Laboratory) and flown coast-to-coast in 1953, was the Space Inertial Reference Equipment (SPIRE) navigation system (Fig. 4). The system included five gimbals, had a diameter of 5 ft, and weighed 2000 lb. The accuracy of the system was about 0.5 n mile/h.

In the next 20 years, efforts continued to improve the accuracy of GN&C systems while reducing their size. Mechanical implementations of inertial navigation systems reached their peak in the 1970s with the development of the Advanced Inertial Reference System (AIRS) guidance system for the Air Force MX missile, which is shown in Fig. 5. The size of the packaged ball is 21 in. in diameter.

As the diagrams in Fig. 6 show, the early implementations of control systems were also based on mechanical instrumentation. Synchros, motors, tachometers, and mechanical differentials were used. However, the improving performance using mechanical instrumentation had its limitations. The mechanical complexity needed to meet the performance requirements increased the difficulty of

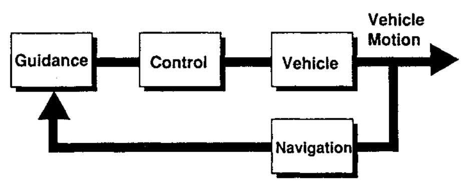

Fig. 1 Classic GNC block diagram.

Eli Gai got his B.Sc. and M.Sc. degrees in Electrical Engineering from the Technion, Israel, and a Ph.D. degree in Instrumentation and Control from the Massachusetts Institute of Technology. Since 1975 he has worked at the Charles Stark Draper Laboratory, Cambridge, Massachusetts, in analysis and design of navigation and fault tolerant control systems. He was the Manager of the Draper IR&D program and the Director for Decision and Control Systems and is currently the Director for Tactical Systems. He has published over 20 papers in reference journals and gave the Plenary Session presentation at the 1993 AIAA Guidance, Navigation, and Control (GNC) conference, which was the basis for this paper. He is a Fellow of the AIAA was the Chairman of the AIAA GNC Technical Committee and Deputy Director for Mechanics and Control of Flight.

EDITOR'S NOTE: This manuscript was invited as a History of Key Technologies paper. It is not meant to be a comprehensive study of the field. It represents solely the author's own recollections of events at the time and is based upon his own experiences.

Received Feb. 20, 1995; revision received July 1, 1995; accepted for publication July 3, 1995.

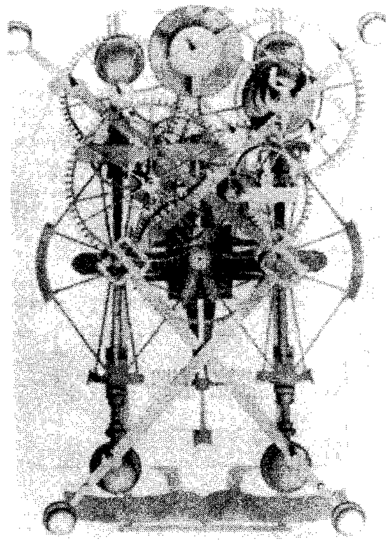

Fig. 2 Harrison clock.

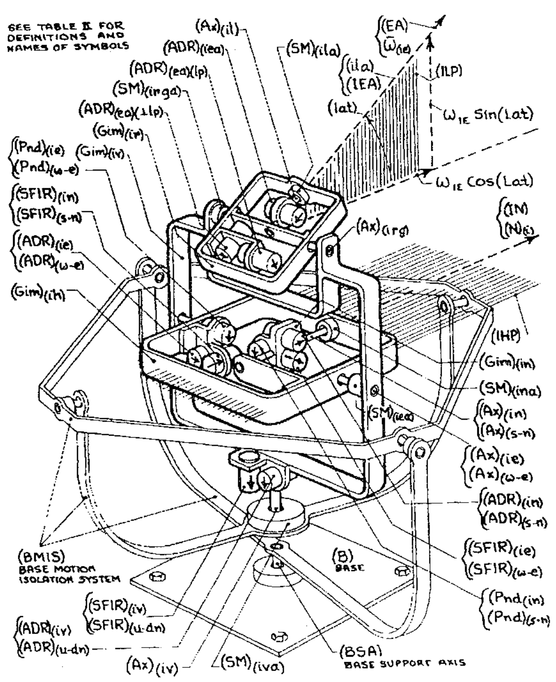

Fig. 3 Mechanical implementation of inertial navigation system.

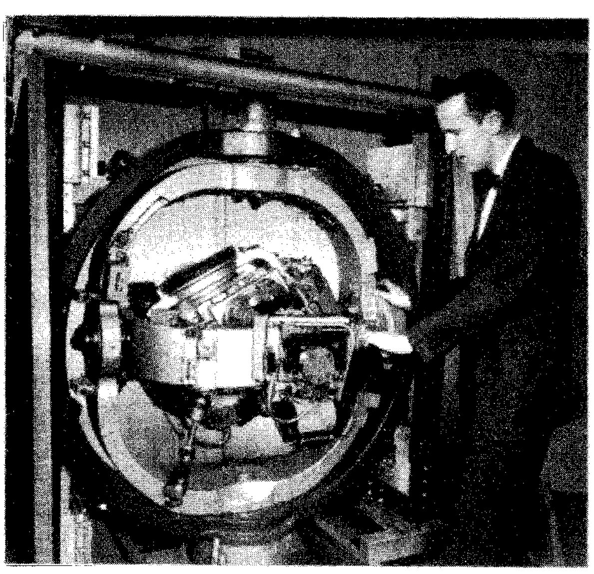

Fig. 4 SPIRE.

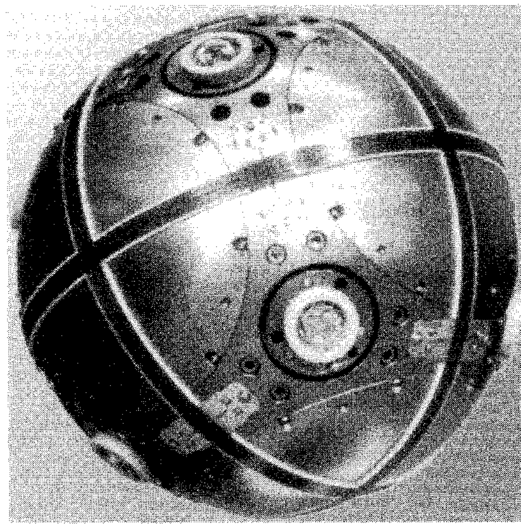

Fig. 5 AIRS guidance system.

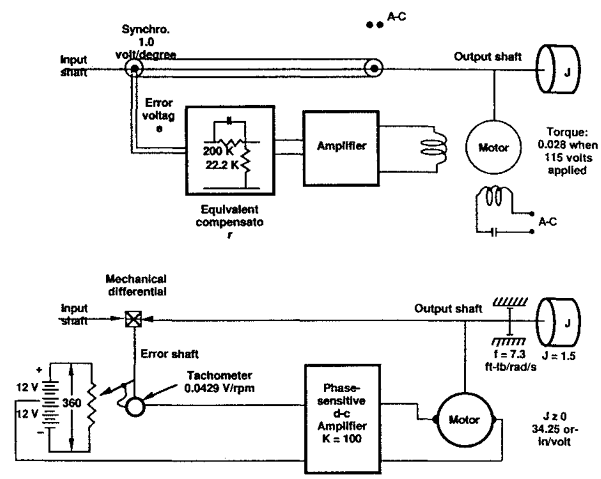

Fig. 6 Early implementation of control loops.

manufacturing the system, created reliability and maintainability problems, and drastically increased the cost. These limitations notwithstanding, the real drive to change the implementation approach was due to advances in electronic technology.

III. Transition: Reducing Mechanical Instrumentation

Although other innovations, such as lasers and fiber optics, gave impetus to the reduction of mechanical instrumentation, the key contributor was the invention of the transistor and later the integrated circuit. The ability to build compact, reliable, solid-state electronics that could meet the requirements of flight equipment was the key driver. The effort to reduce instrumentation went in three directions: strapdown systems, the use of star sensors, and the use of sensors that could measure position directly.

In a strapdown system, mechanical instrumentation is reduced by eliminating the gimbals and creating a coordinate frame in a computer that represents a virtual stable member. The instruments, both gyros and accelerometers, are mounted on the body of the vehicle. Gyroscopic measurements are used to update the inertial coordinate frame in the computer, and the accelerometer measurements are transformed to this frame and then integrated to obtain position. A laser gyro-based strapdown Inertial Measurement Unit (IMU) is shown in Fig. 7. A strapdown inertial system is also more efficient than a gimbaled system in the use of redundant sensors for fault tolerant designs.[4]

The other efforts to reduce the complexity of mechanical instrumentation involve the use of noninertial sensors to aid the inertial package, thus breaking away from the black box concept. One of the major sources of error in inertial systems is gyro drift, since its contribution to the position error increases as a function of t^3. This error can be reduced by updating the inertial system with measurements

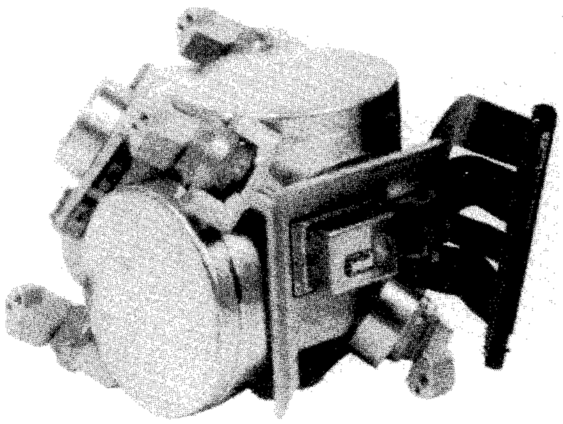

Fig. 7 Sensor assembly for LN-100G.

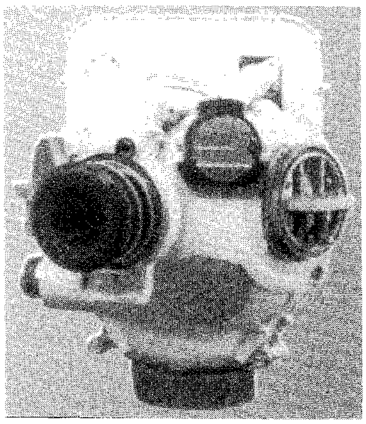

Fig. 8 MK6 guidance system.

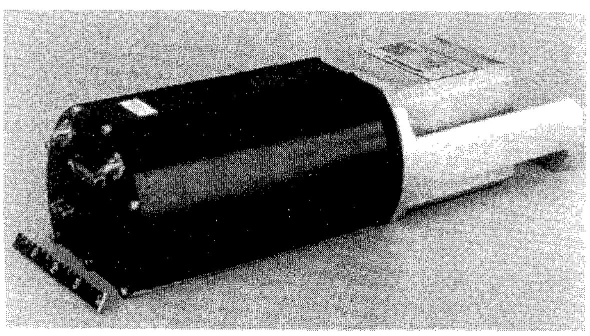

Fig. 9 M-MIGIT GPS/INS system.

of the line of site to a star. Using a star sensor, the growth of the gyro's drift can be bounded, thus allowing the use of gyroscopes with reduced performance. Figure 8 shows the MK 6 guidance system of the Trident II missile (approximately 13 in. in diameter including the case.) It includes a star sensor and two-degree-of-freedom gyros that are much simpler than the third-generation gyros (TGG) used in the AIRS guidance system.

The third method to reduce the complexity of mechanical instrumentation is to aid the inertial system with position measurements. This reduces the requirements on both gyros and accelerometers, allowing the use of solid-state instruments. The introduction and acceptance of the global positioning system (GPS) constellation led to a proliferation of smaller and less expensive, precision GPS/inertial navigation system (INS) navigation packages (Fig. 9).

Since denial and jamming were not a primary concern, the use of aided inertial systems in civil aviation preceded the military by almost 30 years. Radio information from Very high frequency navigation systems (like Loran C) was contained with inertial measurement unit inputs to provide autopilot functions. Later advanced flight management computers (FMCs) used those inputs to provide mission planning and replanning interacting with air traffic control updates.

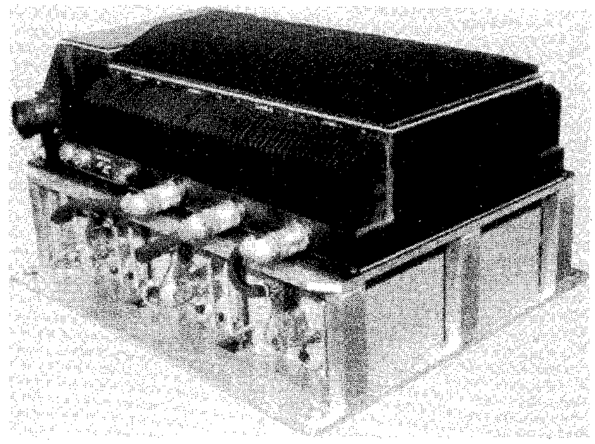

Fig. 10 F-8 fly-by-wire redundant computer.

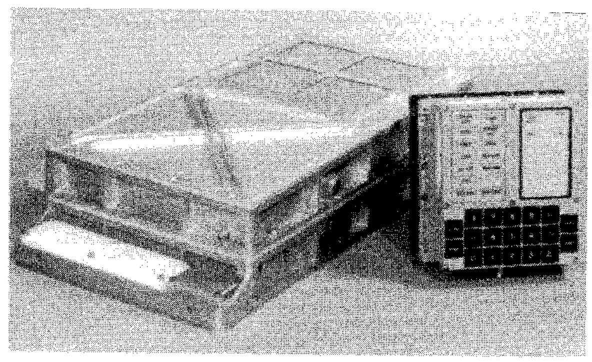

Fig. 11 Apollo computer.

In the development of control, the introduction of solid-state electronics led to fly-by-wire flight control systems. The first fly-by-wire flight control systems (like in the F-16) used analog electronics that were later replaced by digital implementations. Figure 10 shows the triple-redundant computer system that was built for the NASA F-8 aircraft, which was the first digital flight control system that was flown without any mechanical backup.

IV. Intelligent GN&C Systems

Like the transition from all-mechanical implementations to aided systems, the emergence of intelligent GN&C systems was driven by technology innovations, specifically, the continuous improvements in digital computation. Figure 11 shows the computer that was developed by Draper Laboratory in 1964 to implement the GN&C functions of the Apollo spacecraft. That computer had 38 kbyte of memory and 2 kbyte of RAM, three orders of magnitude less than a current midrange desktop computer.

It is well known[5] that in the last three decades there has been a four-order-of-magnitude increase in the speed and memory capacity of digital computers. These increased capabilities allow the use of more accurate guidance and navigation algorithms, as well as more sophisticated compensation for sensor errors. In addition, they enable the development of systems with additional attributes that did not exist in classical GN&C systems. These new, augmented systems, which include additional sensors as well as additional closed outer loops, are referred to as intelligent GN&C systems. The added capability that defines an intelligent GN&C system is its ability to achieve mission objectives in a changing, uncertain environment. By environment, we mean both the internal environment (i.e., failures, damage, or excessive use of resources) and the external environment (i.e., weather, obstacles, or military threats). This is an important addition to classical GN&C systems, since those systems either could not deal with such changes at all (in unmanned systems) or left it to the human operator to deal with them (in manned systems).

This new capability is implemented by adding an outer loop to the classical GN&C system, as shown in Fig. 12. This outer loop includes three major blocks. The first one consists of the environmental sensors. The other two, data fusion and automated planning and decision making, are both implemented in software. The intelligent GN&C system is, therefore, composed of sensors that sense the state of the vehicle and its environment and software blocks that process that information and pass the commands to the actuators. It should be emphasized that intelligent GN&C systems are not only useful in unmanned vehicles but also can be used as decision support systems (sometimes referred to as associate systems) in piloted vehicles, thereby reducing pilot workload. The two additional software blocks that are included in the outer loop need further discussion.

Data fusion is a three-step process. In the first step, the data are collected and relevant information is extracted. The second step is to combine the data that come from different sources representing different aspects of the environment. The third step is to provide an assessment of the state of the world. This three-step problem is a constraint optimization problem for which optimal solutions have not yet been found. Approximate solutions using heuristics, algorithms, expert systems, and neural nets have been implemented with modest success.

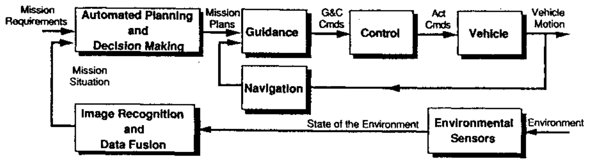

Fig. 12 Block diagram for intelligent GN&C system.

Fig. 13 Pilot's associate cockpit.

Real-time planning is the determination of an ordered sequence of actions that are required to best achieve mission objectives given the state of the vehicle and its environment, as well as operational constraints. Although this problem is essentially a constrained, statistical optimization problem, more progress has been made toward solving it than the data fusion problem. Several approaches have been used to address the difficulties of this problem; the most common one is hierarchical decomposition. Using this approach, the planning problem is partitioned into several levels with different planning horizons so that the plan at each level can be generated at a different pace. In solving the planning problem at each level, optimality is not necessarily required; satisfactory solutions are generally acceptable. Since replanning during a mission is a critical function, depth-first solutions are preferred. In depth-first types of solutions, the best available solution is stored, and additional iterations try to improve it. Figure 13 shows the cockpit with a pilot's associate that was developed for Advanced Research Projects Agency (ARPA) that includes both data fusion and automated mission planning.

V. Distributed GN&C Systems

The GN&C systems that have been discussed so far have been designed to guide, navigate, and control a single vehicle. As they have in the past, technology advances will allow us to generalize intelligent GN&C systems to distributed GN&C systems in which many distributed assets are managed. Technology advances in data networks and switching techniques that improve both the connectivity and the capacity of networks will enable us to solve distributed GN&C problems.

Consider the situation in Fig. 14. It contains many different assets on the ground, in the air, and in space. Each asset has knowledge of its position and status, and the capability to transmit and receive information. The distributed GN&C problem is to manage these distributed assets to perform their collective mission in a way that best satisfies specified mission objectives in a dynamic environment.

The essential problem is to close the loop on multiple distributed assets. The solution to such problems is composed of four elements. The first element consists of the sensors that measure the state of the system. The emphasis here is on the development of very small, inexpensive sensors. Such sensors already exist. Micromechanical inertial sensors (Fig. 15) and miniature GPS receivers and antennas are examples. The second element is the computer hardware. The emphasis here is on the development of computers with sufficient throughput and memory. Continuous improvements in processors and memory technologies, coupled with innovative parallel architectures, are expected to provide the computational hardware needed to solve this problem at a reasonable cost. The third element consists of secure, reliable data networks providing the necessary connectivity and channel capacity.

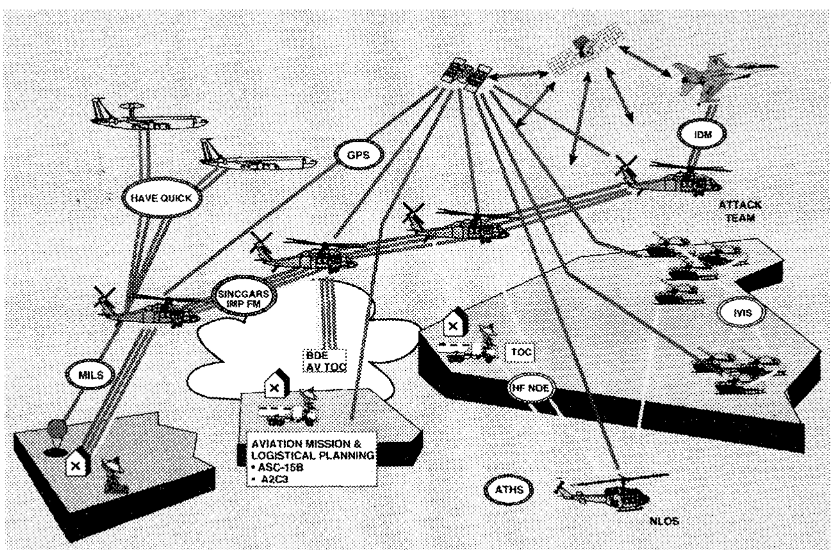

Fig. 14 Distributed GN&C.

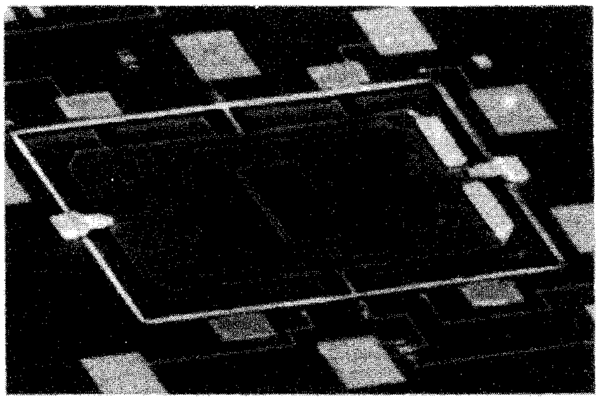

Fig. 15 Micromechanical accelerometer.

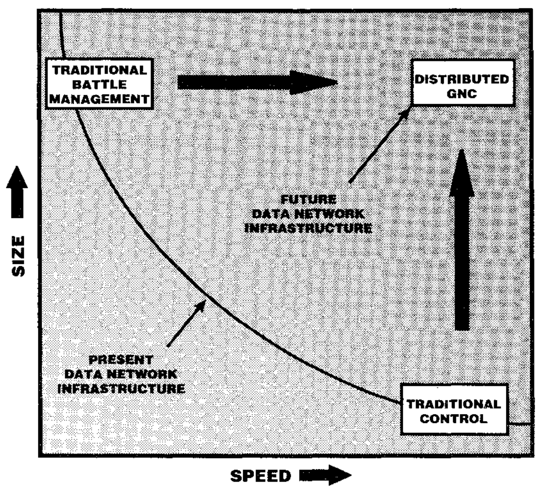

Fig. 16 Effect of data network.

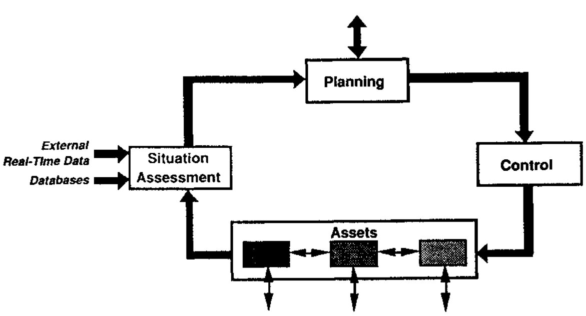

Fig. 17 Recursive loop.

The development of the global grid, employing parallel switching capabilities in the form of asynchronous transfer modules (ATM), is expected to make the development of distributed guidance technology a reality. The fourth element is information management in the form of algorithms and software that will integrate the three other elements and generate the commands required to close the loop (in fact, multiple loops) around the system. It is in this area that most of the development is required. The opportunities here are enormous. The question, however, is, why this should be viewed as a distributed guidance problem and not simply a classical command, control, communication and information (C^3I) problem? The answer to this question is shown in Figs. 16 and 17. Figure 16 shows the effect of data networks on the number of assets and rate of feedback plane. Future data networks will allow us to control many assets with a very high rate of feedback; the same rates at which guidance problems are currently solved. It seems natural, therefore, that techniques similar to the ones used for guidance problems could be modified to deal with the distributed guidance problem. Figure 17 shows the recursive loop that will be used repeatedly in hierarchical, distributed systems. The figure shows several different kinds of assets that have to be managed. Measurements on the state of these assets are taken and transferred to a situation assessment function, where they are fused with external real-time data and information from stored databases. All of this information is processed to provide the best current assessment of the state of the system. This function is the generalization of the navigation function in classical GN&C systems, since it provides position and velocity information for the various elements of the system, as well as information with respect to the ongoing plan. The estimated state of the system, together with external commands from higher levels in the hierarchy, represents inputs to the planning function. This function is the generalization of the classical guidance function; instead of generating a single desired trajectory, it generates a comprehensive plan for all elements of the system. Finally, this plan goes into a control function that monitors the progress of the plan and provides the commands thatare required to continue to follow or modify the plan.

Many known problems fall within the domain of distributed GN&C systems. A simple example is a guidance system for a precision strike weapon in which the targeting function is separated from the weapon itself. The weapon includes a guidance system to reduce the dispersion, but the targeting is done from a separate location.[6] Horizontal integration of Army assets, sometimes referred to as synchronized maneuvers, is another example. So, too, is the solution of the combat identification problem. On the nonmilitary side, problems like air traffic control and the intelligent vehicle highway system also belong to this domain.

VI. Conclusions

This paper has reviewed the development of GN&C technology from its early days, when mechanical instrumentation was the only way to solve the problem, to the present time, where information technology allows us to develop much more capable intelligent GN&C systems. It also looks to the future and our ability to solve a new class of distributed GN&C problems. The many applications, both military and nonmilitary, of distributed GN&C systems represent both the challenge and the new opportunity that faces us today.

Acknowledgments

This paper was written after many discussions with my collegues and friends: Milton Adams, Robert Beaton, Paul Motyka, and James Harrison. Stephen Osder, as an associate editor, made valuable suggestions to improve the paper. James Harrison also contributed to editing and improving the quality of the manuscript. This review of the development of the field of GN&C is based on the author's views and is strongly influenced by his 23 years in Charles Stark Draper Laboratory and the Massachusetts Institute of Technology.

References

[1]Anon., "The Dawn of Modern Navigation," *The Economist*, Dec. 1992.

[2]Callander, B. D., "Zulu Time," *Air Force Magazine*, Vol. 74, No. 1991, pp. 79–81.

[3]Draper, C. S., "Self Contained Systems for Control Navigation and Guidance," Charles Stark Draper Lab., Rept. CSDL-R-1442, Cambridge, MA, Feb. 1981.

[4]Deyst, J., Daly, K., Harrison, J., and Gai, E., "Fault Detection Identification and Reconfiguration for Spacecraft Systems," *Journal of Astronautical Science*, Vol. 29, No. 2, 1981, pp. 113–126.

[5]Robinson, C., "Information Technology Runs User's Bandwidth Bandwagon," *Signal*, Vol. 48, No. 6, 1994, pp. 35–38.

[6]Setterlund, R., "Exploiting Accurate Relative Targeting for Precision Strike Applications," CDSL Rept. P-3408, Sept. 1994.