AUTOMATED CONTROL OF MULTIPLE GROUND VEHICLES

William A. Rice
Chief, Telemetry Branch
National Range Operations Directorate
White Sands Missile Range, NM

ABSTRACT

The Drone Formation Control System (DFCS) was developed by IBM, Federal Systems Division in 1976 under contract to the US Army White Sands Missile Range (WSMR) to provide precise automatic closed-loop control for multiple target aircraft.

The unique DFCS distance measuring equipment (DME) data link allows for both range measurement and the transmission of both command and telemetry data on a single frequency (915 MHz).

The DFCS is controlled by a federated chain of microprocessors linked to a large scale IBM System 360 Model 75. The unique data link embedded in a system totally driven by software allowed the DFCS to be modified for automatic control of multiple ground targets as well as aerial targets.

This paper briefly describes the DFCS and the modifications performed for ground target control. The DFCS RF modulation/demodulation technique is emphasized.

INTRODUCTION

Projected requirements in the early 1970's for multiple repeatable target presentations and precision formation flying led to a conceptual study at WSMR to determine what kind of control system could be used. The introduction of the U.S. Amy's Air Defense Patriot missile project and the U. S. Navy's counterpart AEGIS missile program, both multiple target engagement missile systems, lent particular impetus to the effort, in that foreseeable sophisticated target support would be required for testing those weapon systems. WSMR had achieved a measure of success in formation flying of two targets with an existing UHF manual target control system but control of more than two aerial targets was difficult, if not impossible, and formation precision did not satisfy requirements. The U.S. Navy had built an automatic prototype system for two aerial targets but abandoned the program due to prohibitive expense of the airborne equipment. The Navy had also demonstrated a capability for controlling two targets in formation using airborne television. Both Navy systems employed a UHF command/control system. A review of existing target control systems indicated that no existing system, however, modified could meet the requirements. A technique of Distance Measuring Equipment (DME) employing federated microprocessor application appeared to have the best chance of satisfying precision tracking and control accuracy requirements and also of handling a large number of targets simultaneously. The DME approach was selected after a successful feasability demonstration during a program conducted by IBM-FSD called TAFFE (Target Automatic Formation Flying Equipment). The TAFFE program utilized hardware which was designed and fabricated by IBM-FSD for the Air Force ALSS (Advanced Location and Strike System) program. Competitive procurement proposals were solicited by WSMR in January 1975 for design, development, implementation and operation of the Drone Formation Control System. The IBM DFCS design was selected and a contract was awarded in June 1975. The DFCS was installed in August 1976 and declared operational, after extensive testing, in February 1977.

A requirement to make a presentation a ten moving ground targets (M-47 tanks) was placed on WSMR in 1979. Full scale target aircraft (QF-102) had been taken off and landed with the system so the ground tracking capability and multipath rejection qualities of the system were well known. Since the DFCS is so totally dependent on software, with the attendant flexibility, the decision was made to modify the system to control ground targets rather than procure a new system. A capability for precise control of up to twelve M-47 tanks was demonstracted in 1981.

SYSTEM CONFIGURATION

The DFCS is a computer directed, ground based guidance and control system. It is structured around an IBM System 360 Model 75 computer system interfaced to a network of federated ground and airborne, microprocessor based, microwave transponders, as well as a system control and display facility. The system was originally designed to automatically track and control up to six target aircraft while maintaining track of up to four additional objects.

SYSTEM OPERATION

Figure 1 is a simplified system diagram showing the signal flow between the central computer, the ground stations, and the target being interrogated. All participants (ground and airborne stations) have a unique address and all ground stations which have the proper line-of-sight to a transmitting station can play any of the roles described below.

The initial step in the interrogation sequence is for the central computer to compare the measured position of the target to the desired position. A series of commands are generated through the particular target's control algorithm and the central computer (CC) assembles a binary message containing these commands. The current geometry is assessed and the CC chooses ground stations to participate in the upcoming interrogation to allow optimum space position measurement as well as optimum antenna patterns for the ground station which will actually transmit the commands and receive the telemetry. The addresses of the ground stations, and the roles these are to play, are inserted in the message along with the message mode or type and the message is transferred to a ground station (GS) co-located with the CC. The co-located GS then modulates this message on a series of RF pulses and broadcasts. Every station (ground or airborne) with line-of-sight to the co-located GS will receive the message and decode it to determine message type and station(s) addressed. Message types and the datalink sequence are depicted in Figure 1.

The first message (1) transmitted is relay select and only the selected relay GS will respond. The chosen relay GS will rearrange the message into a master select message (2) and transmit. Only GS's with line-of-site to the co-located GS may serve as relays. This master select message is also received and decoded by all stations within line-of-site but again only the chosen master will react. The master GS is so named because it will perform the actual interrogation of the target. Optimum antenna patterns are desirable for transmission of command and telemetry data so the station the target is flying most nearly toward is chosen as master. The master GS reconfigures the message into a target interrogation message (3) and transmits. A counter at the master GS is started for purposes of making a direct range measurement upon response from the target.

The type 3 message contains addresses of a number of stations required to perform several functions. The chosen target will decode the message, transfer command data to the target autopilot and prepare to relay to the master GS with telemetry data. Three GS's addressed in the message will decode and start counters for purposes of indirect range measurement.

The type 4 message is the response (after a fixed delay) of the chosen target containing telemetry data measurements of on-board parameters and conditions. Upon receipt of the type 4 message the master station stops the range measurement counter thus obtaining data for a direct range measurement. The telemetry data are stored in microprocessor memory for later transmission. Also, upon receipt of the type 4 message, the other three participating GS's stop their counters preserving the measurement for calculation of indirect range. (indirect range is calculated in the central computer utilizing the survey distance between a given GS and the master GS and the delay data collected via the counter.)

Message type 5 is the reply (after a fixed delay) of the first station chosen to measure range indirectly (SLAVE #1). This message contains the value of the counter and some GS conditions and is transmitted to the Master GS. Message type 6 is the same as type 5, only being transmitted to the master by the second station (SLAVE #2) chosen to make an indirect range measurement.

Upon receipt of message type 6, the master GS will insert all collected telemetry and range measurement data into a message to be transmitted to the relay GS (message type 7) for final transmission to the co-located GS and central computer as message type 8. The relay GS was the third GS participating for indirect range measurement so message type 7 differs from type 8 in that this measurement is inserted.

Thus the loop is closed with all command and telemetry data transferred and with data collected to very precisely calculate space position. Four ranges, one directly measured and three calculated, are used to calculate space position. Telemetered barometric and radar altimeter data are utilized to improve the space position solution at low altitudes.

GROUND VEHICLE CONTROL

A number of decisions had to be made when the task was levied to modify DFCS for ground vehicle control.

Data Link Ground Station Software. Since the data link (ground and airborne stations) is totally controlled by microprocessor software it was decided to use the message types and lengths utilized for aircraft even though the number of commands and the amount of telemetry data required for ground vehicles were far less than for aircraft. The longer messages precluded using an interrogation rate of ten per second, as used for aerial targets, because of time available on the time-shared single frequency data link. Three interrogations per second was found to be adequate for these ground vehicles (M-47 tanks). This rate allowed enough time on the data link to accommodate twelve vehicles, two over and above the requirement of ten, and also avoided a lengthy and expensive rewrite of ground station software.

Closed Loop Control. All aerial targets controlled by the DFCS are interfaced with autopilots which vary in sophistication but do control most basic aircraft functions. Examples of such functions are: altitude hold; airspeed hold; heading hold; and coordinated turns. This means that many loops can be closed within the aircraft thus relieving ground control systems of many tasks. Experience with aircraft indicated that some closed loop control would be desirable for ground vehicles. Since the DFCS vehicle transponder is equipped with a microprocessor with excess capability over and above the transponder task (Z-80), and software would require some modification, the decision was made to incorporate some closed-loop functions within the transponder Z-80 microprocessor and call it an autocontroller.

SYSTEM DEVELOPMENT

The M-47 tanks which were available were equipped with control actuators for brakes, steering, and throttle. Some of the vehicles were interfaced with a VHF radio tone control system for manual remote control of a single vehicle. No telemetry data concerning vehicle performance was available and the vehicles were controlled by driving on a straight road within view of a television camera. For precise automatic control, the existing actuators were retained and a number of telemetered functions were added such as speed, throttle position, brakes on/off, engine RPM, steering rod position, and tank manned/unmanned. Since the vehicle was not capable of great velocity (20 mph), calculation of velocity vector heading was not sufficient for a good definition of vehicle heading so a heading gyro was added.

The transponder (autocontroller) was programmed for a heading hold function and a speed hold function. This was done by use of the heading gyro and coupling the throttle position data with the speedometer data. Both on-board functions proved to be more precise than attempting to close the loop through the central computer. The autocontroller was also programmed to provide fail-safe functions such as automatic shut-down in the event communications with the central computer were lost.

The method of automatic control adopted was similar to that for aircraft in that a closed control plan consisting of geodetic survey points describing a racetrack road is stored in the central computer. A mathematical reference point is driven around the control plan at the desired velocity and the targets are controlled to precise off sets from the reference point. This is as opposed to attempting to control each target with respect to each other target greatly simplifying the algorithm. The major problems in developing the software for the central computer were changing the update rate for the data link, accommodating control of twelve vehicles instead of six, and developing a suitable control algorithm. Development of the control algorithm was made especially difficult because the controllability between individual tanks varied greatly, orders of magnitude more than target aircraft. Control parameters and the control envelope was finally defined by empirical means by collecting a vast amount of data on the fifteen tanks interfaced for DFCS control.

The tanks are controlled on a bladed surveyed racetrack five miles in length. Typically the system can keep the vehicles within ten feet of racetrack centerline while maintaining required vehicle spacing within ± 20 feet.

RF MODULATION/DEMODULATION TECHNIQUE

The DFCS RF modulation/demodulation technique was designed to provide the most possible protection against multi-path error. This was done not only to preserve the accuracy of the ranging or DME data, but also to provide as error free command and telemetry data as possible. This was accomplished by establishing a complex waveform and designing the means to decode it.

The technique is to Bi-Phase modulate the reference RF carrier corresponding in time to a generated digital coded signal train, the composite of which forms a coded series of pulses of specific time duration which are transmitted in burst fashion. As can be seen from Figure 2, a synchronizing preamble consisting of three uniquely coded pulses, one 12.7us and two 3.1us in duration, is first generated. The first pulse performs the message synchronization function while the following A and B pulses are used to establish signal acceptance level criteria as a safeguard against multi-path. Data is then transmitted by time alternating the two Bi-Phase modulated A and B pulse codes in a 4-ary pulse position modulation (PPM) technique. The method involves burst transmitting the coded pulse at varying times within a 4us time window. The position of the pulse within the 4us window correlates to a Di-bit data value, of which there are four possible combinations (00, 01, 10, 11) for the four possible pulse positions. Referring to Figure 2. The overall operation of the data link message process is as follows. When a data link message is received at the antenna, the RF energy is input into a circulator. The circulator then directs this energy into the receiver/processor unit (RPU) where it is correlated. Correlation is accomplished by the use of three surface acoustic wave devices (SAW). SAW devices are used generally in the analog processing of electronics signals and have applications in color television, radar, sonar and communications systems. The SAW devices utilized in this application are Pi-Phase Shift Keying (BPSK) tapped delay lines (see Appendix A for a description of their operation).

Upon correlation (detection) of the sync preamble, sync pulse is sent to the signal processor which causes it to sync its clocks and counters and prepares to receive data 28.7us after initial detection of the sync pulse. One of the counters which is reset is the counter which will be used to measure elasped time for purposes of range measurement, in the case of ground stations.

The RF symbols following the sync preamble are correlated in a separate section of the RPU and sent to the received data input of the signal processor. The received data bits are combined in groups of 18, two of which are parity bits reflecting error condition, if any, of the other data bits. The two parity bits are stripped off resulting in a 16 bit ‘word’ which is input into internal microprocessor register memory. The microprocessor then processes the received data according to the software program stored in memory. Processing is handled using byte (8 bit) manipulation. The first 16 bit word following the sync contains message length data indicating the length in 16 bit words of the data link message. The succeeding 16 bit word contains both mode (mode has previously been explained as message type) and address information.

The mode byte contains the mode or message type (i.e. relay, master select, target interrogation, etc.) in which the signal processor will operate, while the address byte contains the unique 8 bit address of the desired data link subsystem. The microprocessor will, according to mode, compare the address received to its address; if they compare, the rest of the message will be stored and processed according to the mode selected. If the addresses do not compare, the signal processor will be reset and the rest of the message will be ignored.

Even though each station (ground or airborne) with line-of-sight to a transmitting station will correlate each valid sync pulse, the unique combining of message types or modes with station addresses causes only those stations required for a given situation to respond according to the software stored in the station microprocessor memory.

The use of this technology has spread and should continue to spread in the future. A joint Army/Air Force program between WSMR and Eglin Air Force Base (EAFB) was implemented in late 1980. WSMR loaned EAFB data link equipment to establish a small DME range for tank control. EAFB is developing a miniturized airborne transponder for joint use by the two Test Ranges. Future planned EAFB applications include aerial target control and missile track/destruct functions.

REFERENCES

Rice, W. A., Rehm, K. D., “Drone Formation Control System (DFCS) A New Generation Test Range System”, IEEE PLANS 1978 Position Location and Navigation Symposium Record, San Diego, CA, Nov 6-9, 1978.

Gose, J. B., Reber, T. F., White Sands Missile Range Data Systems Manual “Drone Formation Control System”, White Sands Missile Range, NM, Sept 1979.

Rinando, A. R., “Microprocessor Applications In Control of Aerial Targets”, TECOM Instrumentation Conference, White Sands Missile Range, NM, 28 April 1981.

APPENDIX A

The following description of the operation of the DFCS surface acoustic wave (SAW) devices is extracted directly from the White Sands Missile Range Data System Manual, "Drone Formation Control System", co-authored by Mr. James B. Gose and Mr. Tilo F. Reber, Sept 1979.

"A pair of electrodes are placed at the surface of a piezoelectric material. An electric field applied to this material causes it to expand and contract and these stresses will spread across the surface of the material like a Rayleigh wave. The Rayleigh wave has both longitudinal and traverse components, much like ripples on the surface of a pond.

The stresses traveling across the surface in turn produce an internal electric field which can be detected by a similar pair of electrodes at another point on the surface. Thus a rapidly changing electrical signal will cause this type of material to vibrate at the same frequency, and these vibrations will move along the surface of the material at the speed of sound.

If a second pair of electrodes, connected in parallel with the first, is placed at the correct distance from the first pair its electrical field will reinforce the acoustical wave. This requires that the two electrode pairs receive in-phase signals, and be an integral number of acoustical wavelengths apart.

If, in this situation, the leads of one electrode set were reversed, the two electrode sets would produce out-of-phase signals which would cancel each other's surface waves. Similarly, if the phases were the same but the electrode spacing wrong for the given frequency there would be a cancelling effect.

The BPSK tapped delay lines use this principle to recognize coded signals. The input to the BPSK device is a 120-MHz phase-shifted signal. Each phase represents a binary digit. As the signal travels down the piezoelectric wafer, it encounters a large group of evenly spaced electrode pairs. If these electrodes, or fingers as they are called, were all connected in phase it would take a 120-MHz signal without phase shift to get maximum output from them. However, the fingers' input lines are switched so that they form a binary code which must be matched by phase shifts of the input before a maximum signal is produced at the output. In this way the BPSK devices will respond strongly only to an input which has been phase-shifted according to the proper binary code. When this condition is met, an adequately large output pulse will activate a threshold device, as in the case of the synchronization pulse, or a logarithmic amplifier as in the case of the data string."

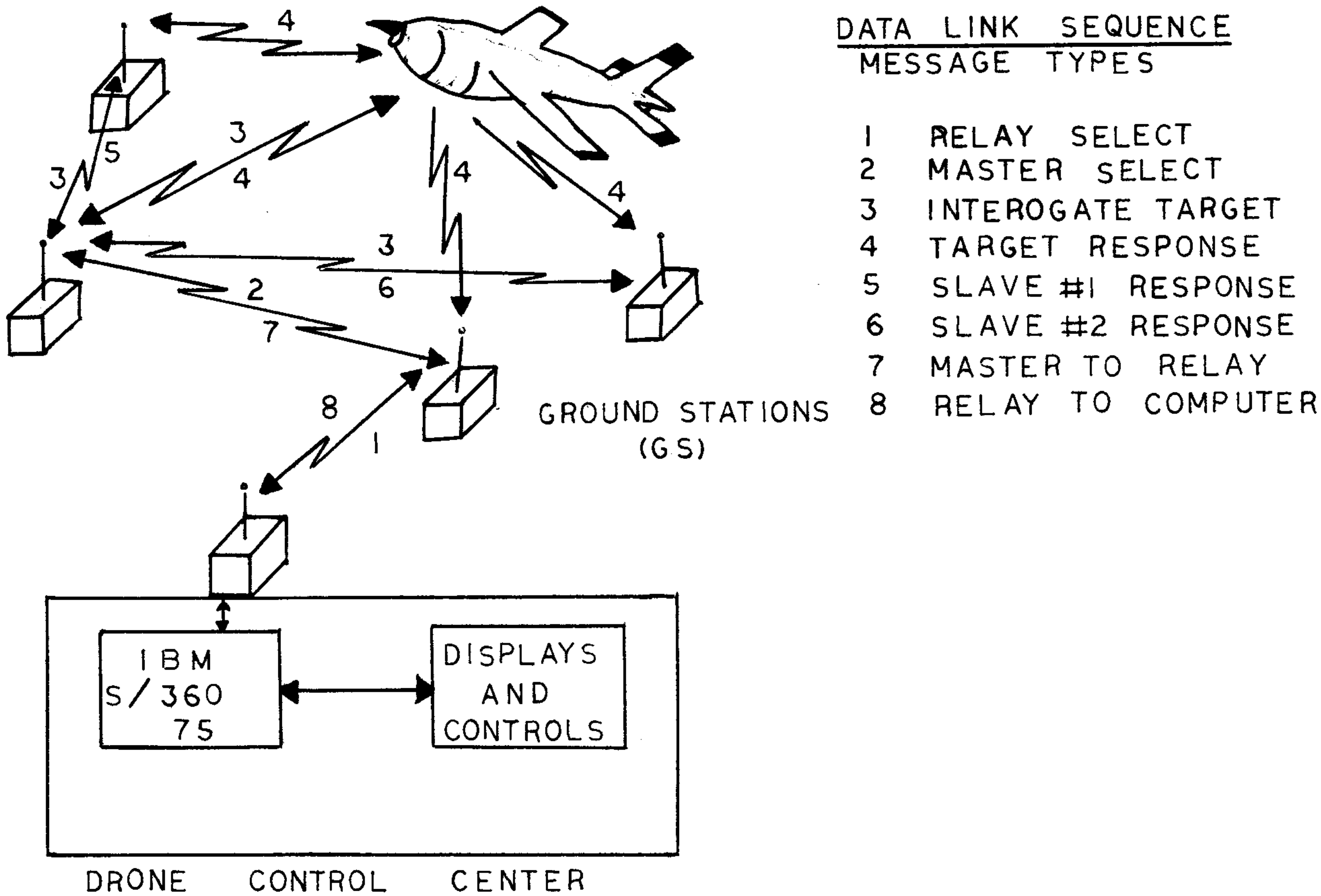
4
3
4
3
5
4
4
3
6
2
7
8
1
GROUND STATIONS
(GS)
DATA LINK SEQUENCE
MESSAGE TYPES
1 RELAY SELECT
2 MASTER SELECT
3 INTEROGATE TARGET
4 TARGET RESPONSE
5 SLAVE #1 RESPONSE
6 SLAVE #2 RESPONSE
7 MASTER TO RELAY
8 RELAY TO COMPUTER
IBM
S/360
75
DISPLAYS
AND
CONTROLS
DRONE CONTROL CENTER

FIGURE 1

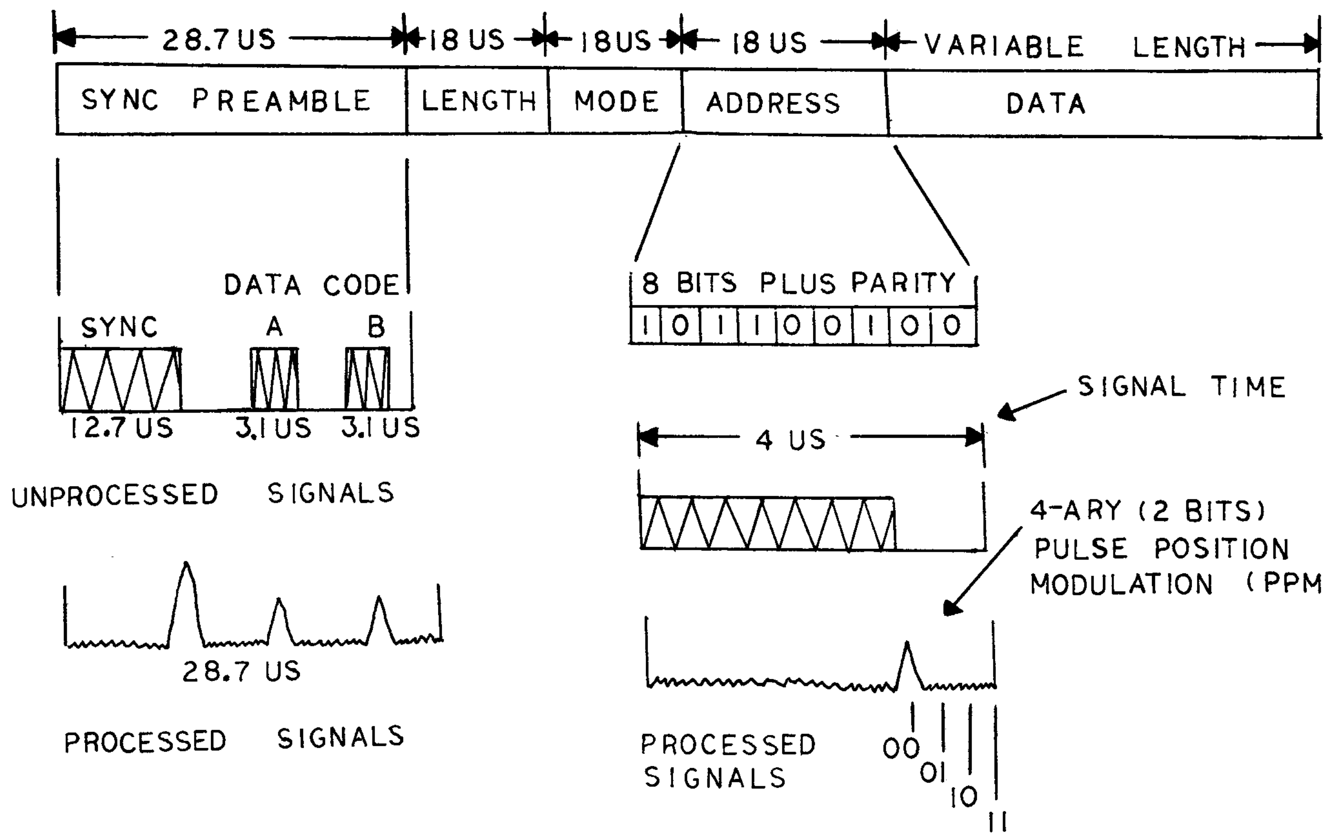

FIGURE 2 DATA LINK SIGNAL FORMAT