TELECONTROL AND TELEMETRY FOR PILOTLESS AIRCRAFT

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INTRODUCTION

General

The Australian Government entered the field of pilotless aircraft development in order to provide target aircraft for guided weapons testing at the Joint United Kingdom/Australian Weapon Testing Range located at Woomera in South Australia(1). Such targets are required to exercise a guided weapon over an adequate range of performance and, at the same time, must be reliable and economic in operation.

The requirement for targets of representative size has been met by converting military aircraft to the pilotless rôle, but for economic reasons the choice is limited to available obsolescent types. Therefore, to meet the extreme limits of performance of the most modern military type, small pilotless aircraft with high performance, readily adaptable to different target rôles, are required.

This paper is mainly an account of the problems encountered in the evolution of the control system for the pilotless Jindivik(2,3) aircraft, which is a typical example of a small high-performance target. The telecommand and telemetry equipments used are described in some detail; the broad results of the first 300 flights are presented, and the future trends for the control of such an aircraft are discussed in the final section of the paper.

History

The Jindivik* was developed as a target aircraft from the experience gained in the operation of the gunnery targets flown in the United Kingdom from the 1920s and, in fact, may be regarded as one of the family of British targets(17)—several of which have been developed in parallel with Jindivik and are currently in service.

The Queen Bee (which was developed at the Royal Aircraft Establishment at Farnborough in England) was a De Havilland Tiger Moth bi-plane fitted with an elementary automatic pilot and a sequence selection

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*Jindivik—an Australian aboriginal word meaning "Hunted One".

radio control system operating in the medium frequency band. The control of this aircraft was virtually fully automatic; it was simply directed by radio.

The QUEEN MARTINET was a later development in this family, and although it was not put into service much of the basic technique later applied to more advanced targets was evolved with this version. Direct selection control equipment was used because of the more rapid response required, and a dual control system for landing was developed. Experience gained when using an observing aircraft to relay flight data to the ground, led to the conception of a telemetry link to transmit to the crew on the ground basic information which would normally be available to the pilot of a manned aircraft.

In 1948 when the specification was issued in the United Kingdom for a pilotless jet aircraft (culminating in the JINDIVIK) the lessons learned with these previous targets were applied to the development of improved telecommand and introduction of telemetry equipment to cover the much greater range of speed and altitude involved, however the basic method of control was retained.

Although JINDIVIK was to be a pilotless aircraft in the true sense of the word, a piloted version was made for the initial test flights; this was known as PIKA ("The Flier")(2), and the first flight trials of the telecommand and telemetry equipment were carried out in this version. Also, some advance was made in the technique of handling the aircraft.

A batch of twelve prototypes of the pilotless aircraft was then made and flown with reasonable success. These were followed by a production batch of an improved (MK. 2) version incorporating the lessons learned with the prototypes.

Jindivik Control System

The JINDIVIK MK. 2 aircraft is a low wing monoplane, 23 ft long and with a wing span of 19 ft. It is powered by an Armstrong-Siddeley ASV3 jet engine and is capable of flying at a Mach number of 0·85 and at altitudes up to 50,000 ft. The aircraft takes off from a detachable trolley and lands on a skid (as shown in Figs. 1 and 2). Conventional ailerons and elevator are fitted, there is no rudder, and the flaps serve the joint rôle of dive brakes and landing flaps. Leading particulars of the aircraft are given in Jane's *All the World's Aircraft*, 1957–1958(4).

FIG. 1. MK. 2 JINDIVIK take-off.

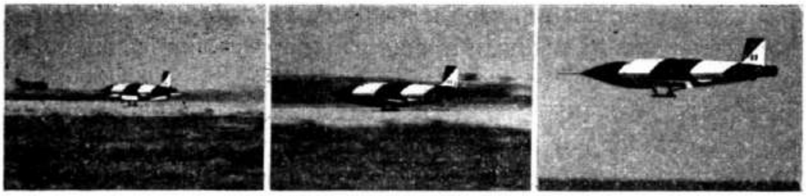

FIG. 2. JINDIVIK MK. 1 landing.

In order to provide a satisfactory service in day-to-day guided weapon trials, a target aircraft must be able to:

(a) Take off at short notice even though the nominal take-off time has been considerably delayed.
(b) Navigate on pre-set courses within fine limits (of the order of ±200 ft in straight and level flight).
(c) Maintain height for a period of 10 to 20 minutes within 1–2% of a chosen altitude.
(d) Fly to a close time schedule (i.e. be at engagement point within seconds of a scheduled time from an arbitrary zero some minutes before).
(e) Perform manoeuvres similar to those of bomber aircraft.
(f) Provide a stable platform for optical and electronic equipment to instrument the engagement, and augmentation equipment to enhance the target's effective size.
(g) Above all, perform reliably and show a reasonable recovery rate, for retrieving trials information as well as for economy.

The method of approach to the JINDIVIK control system can probably best be illustrated by considering the system as a loop and applying the usual servo criteria. The loop (Fig. 3) consists of four elements, namely (i) an auto pilot, to stabilize the aircraft generally, (ii) a telemetry link and a tracking system, to convey basic flight data to (iii), the crew, who

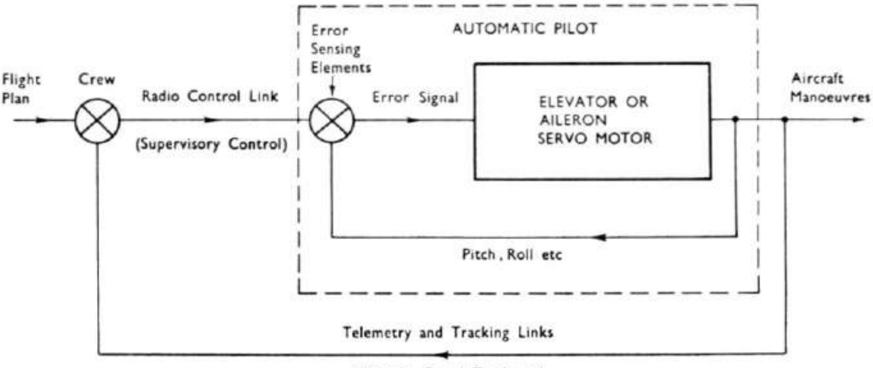

FIG. 3. JINDIVIK control loop.

interpret this data and send commands to the automatic pilot via (iv) a radio control link.

The factors in aircraft stability requiring rapid response of the control surfaces must be the function of the automatic pilot contained within the aircraft—i.e. the automatic pilot must remedy any deficiencies in the inherent stability of the aircraft so that it has long-term stability when left alone, whilst at the same time being adequate for control. The telemetry link, supported by tracking aids, can be regarded as the feedback in the manual control loop, and the quality of this feedback determines the accuracy and range of control that is possible. It is the function of the crew to interpret the telemetry and tracking display to anticipate and judge the strength of the corrections to achieve the required flight pattern, and to transmit the appropriate commands to the automatic pilot. The rôle of the radio control link is to enable the crew to exercise control over the reference levels of the automatic pilot and ancillary actuators.

The nature of the manual control attempted (and the response times of the telemetry), must be compatible with the reaction time of the operator. For example it has been found that operators can adequately control attitude and power for normal flying and for judging the landing, but they need considerable practice to avoid forcing oscillations. To achieve accurate level flying within the degree of accuracy required for trials purposes, however, it has been found necessary to introduce automatic height control, as the total delays in the manual control loop are too great to avoid relatively gentle but sustained oscillation. Manual control in track keeping is easier, as rapid response is not required.

The functions of the four elements in the control system, then, can be summarized as follows:

Automatic Pilot

(a) Providing sufficient damping for short-period modes of oscillation to comply with stressing margins and to provide a steady platform for missile trials equipment.

(b) Providing sufficient damping for the long-period modes of oscillation about the mean demand, to satisfy the navigational and safety requirements.

(c) Maintaining heading, altitude or attitude for level or non-level flight respectively, as demanded, within close limits on a long-term basis, to minimize the work of the crew.

(d) Providing means of performing the appropriate manoeuvres. For manual control purposes a "progressive characteristic" is required.

Telemetry Equipment

(a) Providing a cockpit display for the crew; in doing this the telemetry system must be capable of:

  (i) Maintaining accuracy equivalent to that achieved by normal aircraft instruments, particularly for critical stages of flight (e.g. when the aircraft is brought into the circuit area for

landing and when it is being flown near the permissible speed boundary).
    - (ii) Reliable operation, since it is vital to the successful performance of the mission.
- (b) Furnishing air speed and altitude information for use, in conjunction with tracking aids, in navigating the aircraft.
- (c) Providing engine speed and vertical speed data to facilitate the manual selection of power and attitude to achieve the required air speed and altitude conditions.

The Crew

- (a) Observing the displayed data when the aircraft is flying remotely and judging the timing and strength of controls necessary to achieve the required flight pattern.
- (b) Using direct visual observations and the telemetered speed information to judge the approach and round-out for touchdown during the landing phase.
- (c) Gauging the performance of the aircraft at all times and taking such emergency action as may be necessary.
- (d) Controlling the missile trials equipments as required for the particular trial.

Radio Control Link

- (a) Providing a method for the crew to demand pre-set conditions (such as climb, level, glide, etc.) to assist them in obtaining the basic condition required.
- (b) Providing some fully variable controls to give a measure of proportional control over attitude, bank angle and power and a means of signalling small heading changes for accurate track keeping in straight and level conditions.
- (c) Providing dual control facilities.
- (d) Providing a means of operating ancillary aircraft actuators (skid, flaps, etc.) and missile trials equipment.
- (e) Transmitting timing signals for the purpose of co-ordinating airborne and ground missile trial records.

This brief discussion of the overall control system serves to introduce the two main topics—telecommand and telemetry. The telecommand system is regarded as including the automatic pilot, the radio control link and the crew, and the telemetry section covers the instrumentation of test flights as well as the system in use for control purposes.

TELECOMMAND

Automatic Pilot

When the requirement for small high-speed pilotless aircraft became known a special design of automatic pilot for the rôle was undertaken in the United Kingdom. Available equipments were designed for long life in the control of large military or civil aircraft with stringent performance requirements associated with bomb aiming, passenger comfort, etc., and hence they were, in general too expensive and not particularly adapted to the pilotless target rôle. In addition the small high-speed aircraft presents a rather different stability problem from the larger aircraft. The automatic pilot developed (known as the RAE type B) has been applied successfully to several target aircraft.

JINDIVIK *Automatic Pilot*—Angular rate, position and integral signals for all three axes can be generated within the JINDIVIK automatic pilot and, in addition, a barometric instrument is used to produce a signal proportional to height deviation from a chosen altitude. The signals, in the form of d.c. voltages, are mixed, amplified and used to control position servomotors directly geared to the elevator and aileron control surfaces (as shown in the simplified block schematic of the pitch and roll channels, Figs. 4 and 5).

The basic error-sensing element in each axis is a rate gyro which provides signals relatively free of cross-coupling effects; and, generally, the angular position and integral (or trimming) terms are derived from the rate signals. In addition, a gravity-monitored gyro, with pitch and roll pick-offs fitted, is used as a reference.

Without the attitude reference in the pitch channel any imperfections in the rate signal would result in equivalent rate response of the aircraft; hence if a small misalignment existed the attitude would change continuously. To overcome this effect the attitude error signal derived from the vertical gyro is used to precess the rate gyro in the direction required to reduce the error. Any continuous drift in the integrated rate signal will, therefore, simply result in a small attitude error; similarly, when a fixed degree of elevator has to be applied to maintain an attitude (i.e. to trim) this is obtained at first at the expense of an attitude error, which is subsequently reduced to zero as the rate gyro is precessed in the above manner. When the aircraft is on the ground prior to take-off the integrators are, of course, disconnected (as the aircraft cannot respond to control surface movement) and in this case the pitch and roll position signals from the vertical gyro are used directly.

The height control signal is obtained by enclosing a sample of air, at the existing static pressure on demand of "level flight", and thereafter measuring the difference between the enclosed air and static pressures. To overcome pressure changes in the trapped air, caused by temperature drift, the bulk of the air is contained in a vacuum flask, by which means the height drift is held to a very low figure (about 30 ft/min). When level flight is demanded the height error term is used, instead of the attitude signal from the vertical gyro, as the reference for monitoring the drift of the integrated pitch rate signal and for providing the elevator trim. It is unnecessary to provide a basic reference in the aircraft to monitor the performance of the yaw rate gyro and the associated integrating networks;

the tracking equipment and the action of the crew in applying heading corrections provide this basic reference.

The way in which angular and height error terms are used to position the control surfaces, and the servomotor responses is covered in some detail in the Appendix, where the automatic pilot equations are given.

Table 1 taken in conjunction with Figs. 4 and 5 gives a qualitative idea of the use of these signals.

Table 1

Use of the error terms

Condition	Error terms	Main function
		Elevator
Take-off	Rate of pitch	Damping and rapid response to demands
	Pitch position	Attitude control
Non-level	Rate of pitch	Damping and response
	Pitch position	Attitude control and long-period damping
	Integral of pitch	Elevator trim for zero attitude error
Level	Rate of pitch	Damping—short-period
	Pitch position	Damping—long-period
	Height	Height control
	Integral of height	Elevator trim for zero height error
		Ailerons
Take-off	Rate of roll	Damping and response to demands
	Roll position	Position control
Straight	Rate of roll	Damping—short-period
	Roll position	Damping—long-period
	Yaw rate Yaw position	Bank angle control to maintain a constant heading
	Integral of yaw	Aileron trim for zero yaw error
Turning	Rate of roll	Damping—short-period
	Roll position	Bank angle control
	Height (level only)	Fine control of bank angle

Also, during turns the pitch rate gyro is precessed at a rate computed from true airspeed and bank angle in order to co-ordinate the turn; and the aileron trim pertaining at the start of the turn is held on.

Manual control of the flight is achieved by varying the reference level of the basic sensing elements. As shown in Figs. 4 and 5, the pitch and roll gyros are mounted on platforms which may be rotated with respect to the aircraft to obtain any attitude or bank angle within the range of the automatic pilot. Several pre-set positions of the pitch platform—representing mean attitudes for climb, level, descent and glide—are provided to

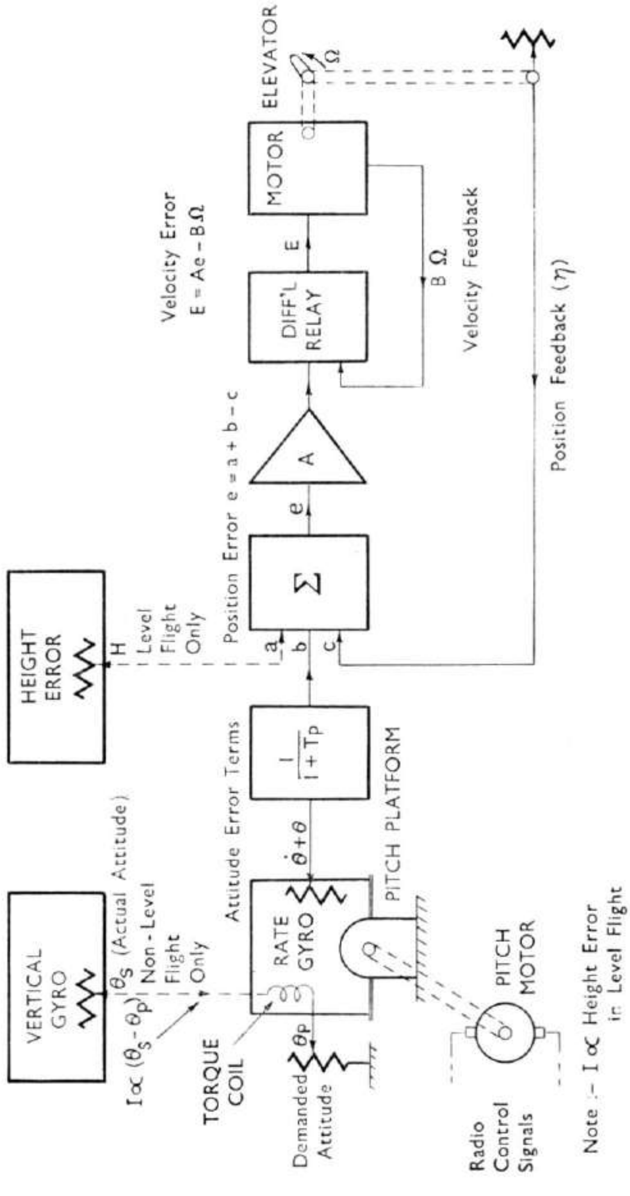

Fig. 4. Pitch channel.

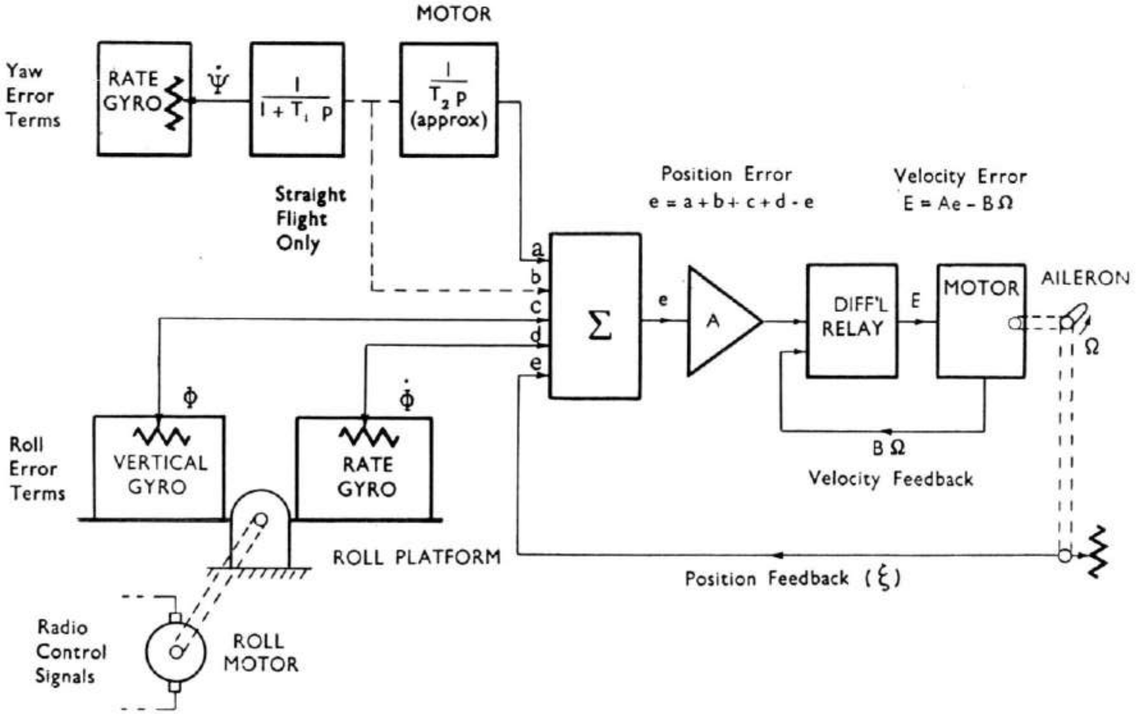

FIG. 5. Roll and yaw channel.

assist the crew, who then make finer adjustments on the basis of the telemetry information. To facilitate accurate course keeping, a method of demanding fine changes of heading is provided which changes the datum of the basic heading reference (i.e. the integrating yaw rate gyro) in small steps.

Some commands are generated automatically by contacting devices within the aircraft to initiate certain manoeuvres more appropriately controlled in this way; for example, the take-off is effected when the correct airspeed is reached; the aircraft levels out on reaching circuit height after descent; and on touchdown the engine is cut and other necessary controls are operated automatically.

Automatic Pilot/Aircraft Matching—Choosing the optimum ratio between the combined pitch rate and position signal, and the elevator position, involved choosing between improving the damping of the short-period and the long-period modes of oscillation. The long-period (or Phugoid) mode requires a strong position term, as the associated attitude changes are very small, but strengthening the combined signal, however, tends to worsen the damping of the short-period mode.

Also, the integral (or trimming) terms are de-stabilizing factors, and therefore these signals have been made as weak as possible consistent with providing the required trim variations at a sufficiently rapid rate. To cater for some transitions, which in the case of JINDIVIK MK. 2 involve relatively large trim changes (e.g. from level to fast glide when the flaps are lowered), it has been found desirable to apply a bias signal to the control surface, matching the trim change as accurately as possible, to reduce the short-term attitude errors and the subsequent task of the trim circuits in reducing these to zero.

When the height term is introduced, the effect on stability is to shorten the period of the Phugoid, and a compromise has to be reached between the accuracy of mean height control and the damping of this mode.

As co-ordinated turns are performed by precessing the pitch rate gyro (at a rate $\frac{g}{v}.\frac{\sin^2\varphi}{\cos\varphi}$ computed from the true airspeed (v) and the bank angle (φ)), the possibility exists of cumulative errors in attitude arising from errors in the computer. Because of this feature, it is necessary to pay particular attention to the accuracy of this device and this is, in fact, one of the most critical features in setting up and adjusting the automatic pilot. The effect of the height term in forcing rather short Phugoid-type oscillations in level turns has been one of the most difficult problems to solve. In order to achieve stable turns for indefinite periods, with reasonable height control, a weak height signal is fed to the ailerons in the sense to decrease bank angle in proportion to loss of height. The integrating action of the height signal through the rate gyro system means that the bank angle is adjusted to overcome any errors that may exist in the computing system.

The rudder was deleted from the aircraft as an unnecessary luxury, but new stability problems arose when flight was attempted with pitch and roll sensing elements only; the gravity-monitored vertical gyro is an unsatisfactory basic roll reference under these conditions. When the aircraft is not constrained in yaw, any small deviation in roll results in the development of a rate of turn; which, through the action of the gravity-monitor precesses the axis of the gyro away from the vertical in such a sense as to increase the bank angle. As the gravity-monitor is very slow in acting, the aircraft tends to fly in a circle of very large radius. The means of overcoming this effect was to restore the integrating yaw rate gyro to the system and to use it in constraining the aircraft to fly straight by controlling the ailerons. Previously bank angle was the reference for heading but now the order is reversed and heading (or integrated yaw rate) is the basic reference for bank angle, which is adjusted to achieve straight flight.

The rearrangements of the automatic pilot, to suit the aircraft and the type of manoeuvre required, have been undertaken by the experimental method, using some calculations, but mostly the trends indicated by the experience of others in the automatic pilot field, to guide the experiments. Trial installations of each small change have been fitted to the aircraft; airborne recorders have been carried to determine the results; and, after a test flight, the records have been analysed to determine the next step in the programme. The basic work of achieving stable flight over a limited region was concluded relatively quickly by this method, but clearance for full potential performance and manoeuvreability proved to be a very long programme. The final section of this paper contains our conclusions on the possibility of doing this type of task more efficiently.

Reliability has been achieved by paying very careful attention to servicing detail, and we have found that very comprehensive test equipment is justified for this purpose; in fact, it is normal to simulate every flight condition and make quantitative measurements of the error signals and the control surface responses, before the aircraft is cleared for take-off.

Radio Control Link

The factors relevant to the design of systems for the transmission of a number of keyed tones over a radio link have been treated in standard texts on radio communication. However, some of the general principles applicable to the choice of a system for pilotless aircraft control are collected here as background to the following description and discussion of the system in use at the Woomera Range(18).

Methods of Multiplexing—As with telemetry systems, discussed later, the first question in the problem of providing a number of channels is whether the channels are to be available simultaneously (direct selection), in turn (sequence selection) or as a combination of both. The principal factor in this choice is simplicity of the airborne equipment, which should be regarded as a necessary attribute for reliability in service.

In general, direct selection is most suitable when the number of channels is not very great, and sequence selection is applicable to the provision of a large number of channels. In either case, precautions must be taken to guard against elimination or imitation of the signals by noise or interference. The direct selection method is easier to protect against elimination by noise, but to obtain high reliability stringent precautions must be taken against imitation of the signals by noise.

If the argument is limited to the use of conventional mechanically-operated devices (such as relays or uniselectors) for coding and decoding the signal, the time delay, when using a pure sequence selection system, becomes prohibitive. A reasonable compromise for the pilotless aircraft case may be reached by using a combination of the two methods which allows a suitably rapid response and at the same time uses a degree of coding which provides a reasonable guard against signal imitation. Thus a small number of channels available simultaneously may be converted to a larger number, available one at a time, by a simple coding technique adequately performed by relays. To provide for simultaneous control by two operators the whole link may be time-multiplexed at a rate sufficiently low so as not to impair the operation of the relay decoding circuits.

Considering now the provision of the simultaneous channels, the choice of the method of distinguishing the channels reduces in practice to frequency or time separation. The former, known as frequency multiplex, lends itself to the use of filters and detectors in the receiving equipment, while the variations of the latter—including pulse-time, pulse-width systems, etc.—normally involve comparatively complicated electronic circuitry or electro-mechanical synchronous devices. When the present equipment was designed some years ago, filters and detectors were considered to be more reliable devices than a number of vacuum tubes, and it was for this reason that the frequency multiplex method was chosen for use with pilotless aircraft. With the more recent introduction of "ruggedized" tubes, and transistors, etc., this reasoning is open to question.

Choice of tones—The general relationship between the number of signal channels (S), the total number of tones employed (N) and a fixed number of tones (n) used to identify any one channel is

$$S = \frac{N}{1} \times \frac{N-1}{2} \times \frac{N-2}{3} \times \ldots \times \frac{N-(n-1)}{n}$$

The maximum number of signals from a given total number of tones N is achieved when:

$$n = \frac{N \pm 1}{2} \quad (N \text{ odd})$$

$$\text{or } n = \frac{N}{2} \, (N \text{ even})$$

thus a maximum of twenty signal channels are available when 6 tones are used, thirty-five for 7 tones and seventy for 8.

There are some minor advantages associated with using a pair of tones

($n = 2$) to designate a channel when bi-stable relays are to be used in the coding and decoding circuits, and the combination of $N = 8$ and $n = 2$ has therefore been chosen; this combination provides up to twenty-eight channels if all combinations are used. The system is capable of extension to fifty-six channels by the relatively simple change to $n = 3$ if it should be required.

The choice of the tone frequencies in this case resolved broadly into a compromise between high frequencies for reducing the size of the filters carried in the aircraft, receiver bandwidth, and considerations of transmission of the tones from remote control points to the transmitter via underground cables. As the associated filters required are relatively simple, and therefore not very heavy, the comparatively low audio band of 3·2–6 kc/s has been chosen to simplify line transmission. The tones are restricted to one octave, as this minimizes the effect of harmonic distortion and intermodulation products and so eliminates the need to maintain the strict control of linearity throughout the transmission system usually necessary with multi-tone systems(5).

The use of a constant fixed number of tones has the advantages that the number may be checked to protect the system against signal imitation. This introduces some complication to the decoding circuits, and the time delay is slightly increased because of the re-set time involved. However, the excellent immunity from false signals that can be achieved in this way justifies these sacrifices when applied to pilotless aircraft.

Filters and detectors—Having chosen the tone frequencies, the design of the filters reduces basically, to a choice between time delay and rejection of unwanted frequencies. It can be shown(6) that the most satisfactory compromise between these two factors is obtained by using filters with response curves of Gaussian form and that, in this case, the time delay (T) (i.e. the time for a step input to rise from 10 to 90% of the final value) is given approximately by

$$T = \frac{1}{B}$$

where B is the bandwidth of the filter measured at the 6 dB points of the frequency-attenuation characteristic(7). On this basis a bandwidth of 100 c/s is required for a typically suitable time delay of 10 msec.

When using relays for decoding it is desirable that the configuration of the filter, detector and amplifier preceding the relay should be chosen to equalize the overall delay, and the operating and release time, of each tone operated relay. This procedure is justified to reduce the possibility of fleeting false signals arising from differences in these values.

Coding and decoding—Coding for the two-tone system involves connecting the operators' switches to pass the appropriate pair of tones to the transmitter, either directly or by means of relays. There is no need to interlock the switches, as, if more than one is operated inadvertently, more than two tones are transmitted and the signal is rejected.

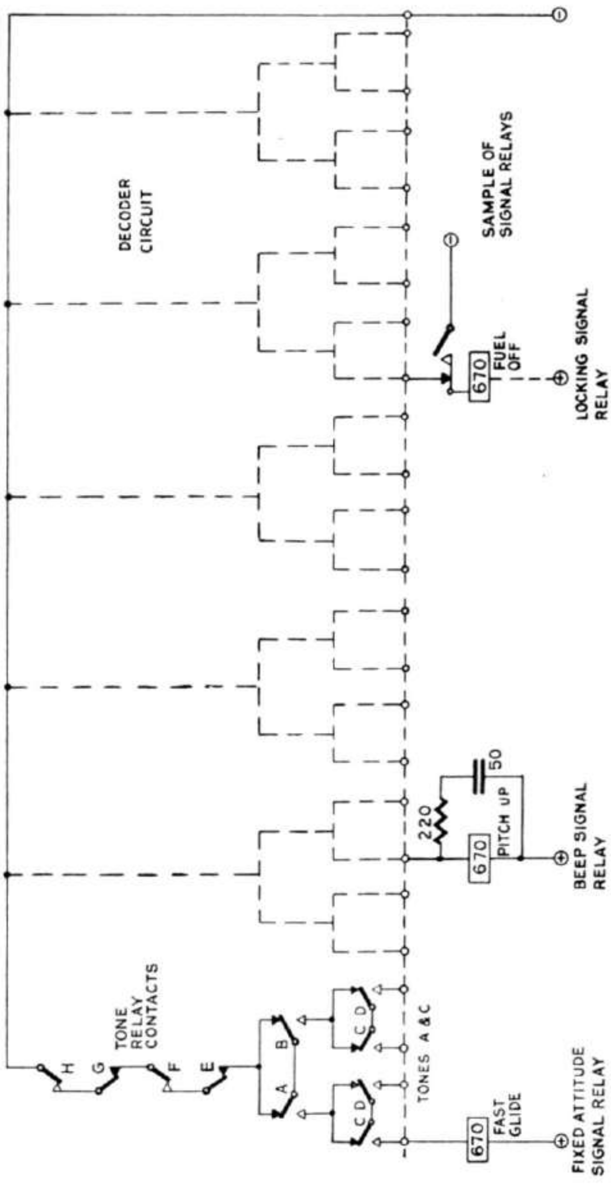

FIG. 6. Decoder circuit.

In the decoder for this system the signal is re-formed by interconnecting contacts of the tone-operated relays in series so that an operational circuit is closed through "make contacts" of the appropriate pair of tone relays and the "break contacts" of the other six, thus ensuring that the signal is rejected if more than two relays are energized simultaneously.

If the simplest interconnexion of contacts is used, it follows that, to re-form all the twenty-eight combinations possible—using 8 tones, two at a time—a total of twenty-eight contacts (involving twenty-eight separate spring sets) would be required, on each of the eight relays. Several circuits can be suggested for reducing the number of contacts required, but, in general, some disadvantage must be accepted. The method chosen for this application is shown in Fig. 6. By using change-over contacts, the number of spring sets required for each tone has been reduced to a maximum of eight. This saving is effected at the expense of deleting four of the channels, and it will be noticed that, if certain of the tone pairs deleted are in fact operated, adjacent output circuits are shorted together.

Transmission of tones—Of the several methods of modulation available f.m. has been chosen because of the relative simplicity of the airborne receiving installation. Provided the signal strength is great enough, the f.m. receiver provides an audio output signal essentially free from noise and constant in amplitude despite signal strength variations, and this feature allows for the use of very simple filters to separate the tones. An additional advantage of f.m. is that, provided strong carrier strength is maintained, the limiting action suppresses weaker interfering signals by the "capture" effect. Furthermore, f.m. has advantages in this application in suppressing the somewhat prevalent impulse noise arising from mechanical/electrical equipment (commutators, etc.) installed in the aircraft.

The choice of the carrier frequency is not very critical, and either the v.h.f. or the u.h.f. band is suitable. It is easier to obtain good all-round coverage when using the v.h.f. band, as the wavelength is nearer to the general fuselage size, and, in fact, the aircraft can virtually be excited as an aerial. In the JINDIVIK application the leading edge of the tail fin has been tapped with a tuned notch to convert it to a narrow band vertically polarized aerial with a good azimuth polar diagram; on the other hand, the v.h.f. band is very congested, and it is only the isolation of Woomera that permits its day-to-day use in this application where freedom from interference is vital.

JINDIVIK *Radio Control Link*—The system shown in Fig. 7 provides for the operation of one of twenty-four signal relays in the aircraft by operation of the appropriate signal button the ground. To achieve this, there are eight sine wave tones available as sub-carriers for the ground transmitter and eight filters to separate the tones in the aircraft; the operation of a signal causes two tones to be transmitted.

A time-sharing system is used to allow two controllers to operate together on one aircraft. A switch at the input of the transmitter modulator operates at 7 c/s, so that the signals from the controllers are transmitted in turn, and when necessary, the aircraft signal relays are slugged so that they do not drop out during the gaps. The tones are generated from a common master oscillator operating at 400 c/s and by distortion a rich spectrum of harmonics of the 400 c/s fundamental is produced. Band-pass filters separate the eighth to the fifteenth harmonics, producing clean sine waves at frequencies 3·2 kc[s to 6 kc[s at 400 c/s intervals. Normally, the filters are short-circuited, but on the operation of a signal switch the short circuits on two of the filters are removed and, hence, two tones are fed to the transmitter. The mixed tones appear at the output of the receiver; they are separated by the filters and, after rectification, energize the appropriate two relays. The relay decoder (Fig. 6) completes the circuit to operate the signal relay corresponding to the two tones detected.

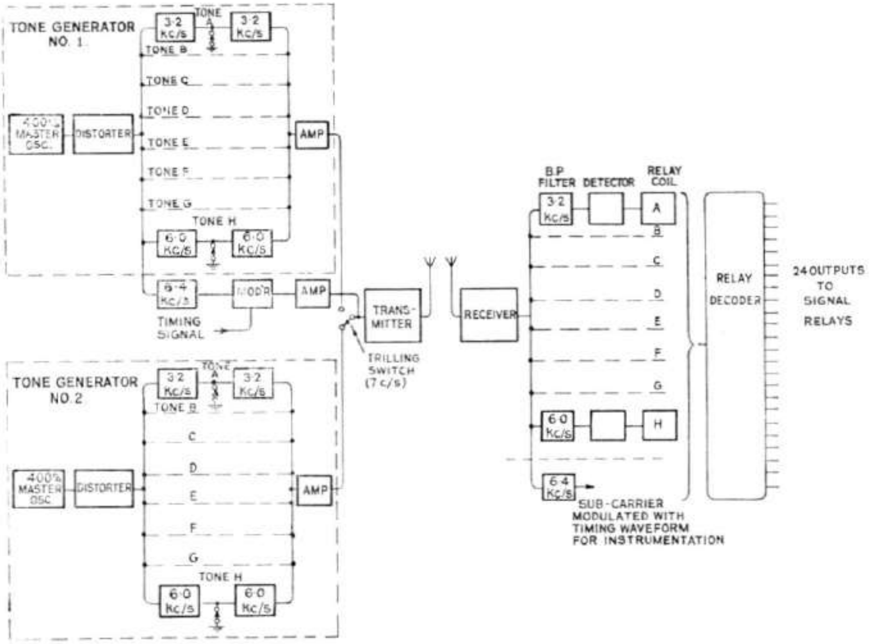

FIG. 7. Radio control link.

The most important features of the system are reliability and freedom from false signals, as proved over a large number of flights. In addition to the precautions already mentioned, two of the tone detectors are made more sensitive than the remainder so that, in the presence of excessive random noise, they should operate first. This tone pair is not used.

To reduce the hazard of interference it is desirable to employ the maximum transmitter power and just sufficient receiver sensitivity to provide an adequate safety factor. Satisfactory results have been achieved using 50 W radiated power and a receiver sensitivity of 2 μV which provides a safety factor of about 20 dB for level flight up to a range of 100 miles at 10,000 ft altitude with the particular aerial system in use.

Use of the signal channels—Of the twenty-four on–off channels, eighteen are available for flight controls and six for the control of special equipments carried for missile trial purposes. The eighteen flight control signals and the signals derived from contacting devices within the aircraft terminate in a relay box which sorts out the signals for control of the reference levels of the automatic pilot, the throttle and ancillary actuators used to operate the landing skid, flaps, etc.

The flying signals fall into three categories, as follows:

(a) "Fixed attitude" signals, of which there are five: climb, slow level, fast level, fast glide and land glide. The corresponding relays are in a locking chain so that one only is always energized. The relay energized causes the pitch platform to drive to a pre-set angle, the throttle to drive to a pre-set position and the ancillary actuators (such as flaps) to operate or release to suit the attitude selected.

(b) "Beep signals" which are effective for the duration of the signal. The up and down signals drive the pitch platform, the left and right signals drive the roll platform, and the throttle open and shut signals drive the throttle actuator. An additional signal called "rumble" is provided to drive the pitch platform and the throttle simultaneously for convenience in overshooting.

(c) Locking signals, such as straight, fuel off and skid down. A high bank turn command changes the maximum available bank angle from 30 to 60° and a fine turn command changes the turn control circuits so that small steps can be obtained in the heading reference.

The Crew

In general, control is divided between two operators—one controlling airspeed and altitude and the other keeping track. The captain of the crew (the skipper) is situated in a flight control centre at the airfield (Figs. 8 and 9); he operates from a control console (Fig. 10) which provides

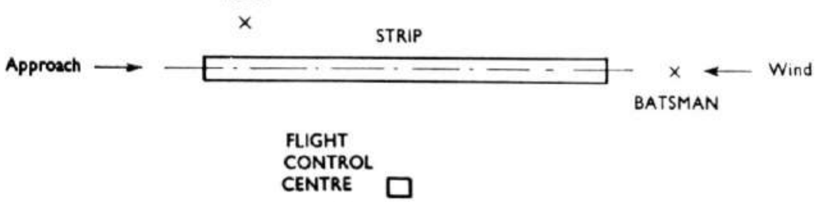

FIG. 8. Landing control.

all the control signals, facilities for switching command to his several assistants, signal monitoring devices, communication equipment and the telemetry display of altitude, airspeed, vertical speed and engine rev/min. In addition, he is furnished with reliable (but relatively coarse) tracking information from several independent sources. When flying remotely, the skipper controls airspeed and altitude, and maintains general supervision of the track controlled by a separate crew member (the navigator) who may operate from the control room shown in Fig. 9, for general flying, or from the range operations room when precise courses are required for missile trials.

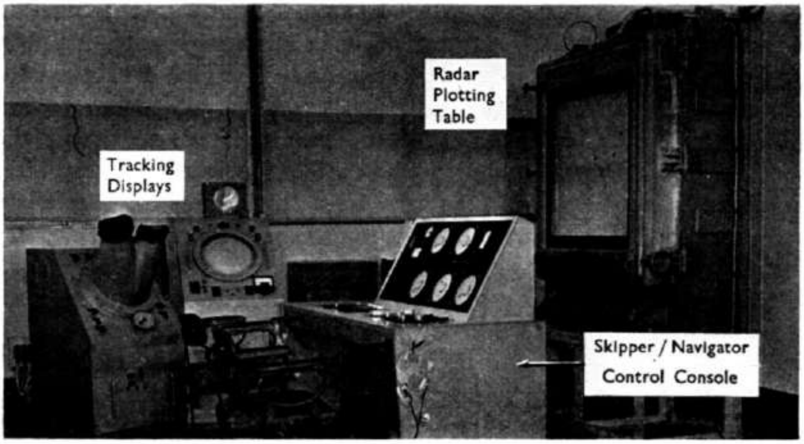

FIG. 9. Control room—flight control centre.

No manual controls are required for take-off except to release a tethering rod on the command of "chocks away". The take-off trolley is steered automatically by the application of gyro signals to the nose wheel and when flying speed is reached the aircraft is automatically released.

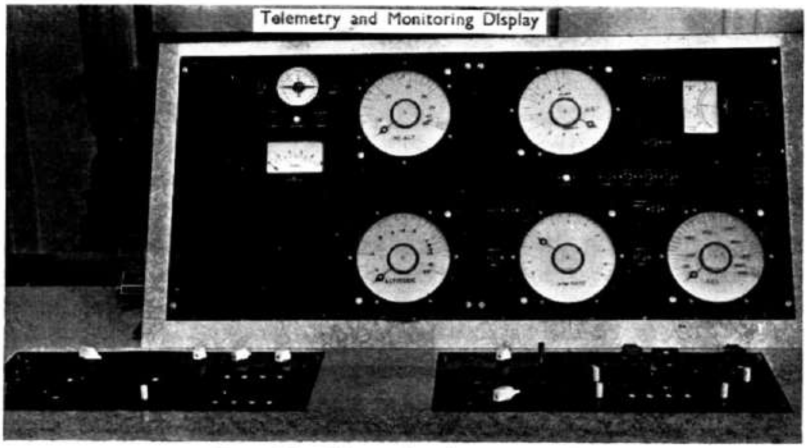

FIG. 10. Skipper/navigator console.

Two additional operators control the landing phase. The azimuth controller (or batsman) is situated in line with the centre of the runway, at the up-wind end, to effect accurate tracking along the line of the strip; and the pitch controller (or pilot) is situated opposite the expected touchdown point to control the aircraft down the glide path and to judge the round-out for touchdown. The batsman has access to turn signals only and he works on visual information exclusively. The pilot is provided with all the flying signals in case overshoot and another circuit is required, but he normally operates on pitch and throttle "beeping" only. In addition to visual information he uses airspeed and engine speed data relayed over the communication network.

From the beginning, experienced aircrew has been used in all phases of control, but, even so, a training period of 2–3 months is required before an individual can be regarded as fully trained. As shown in the following section on results, losses attributable to operators' errors, or lack of judgement, have been almost negligible.

At present the crew is not provided with information on internal behaviour of the aircraft or its components (e.g. jet pipe temperature, oil pressure, undercarriage position, control surface trim, etc.) and they therefore have some difficulty in taking the appropriate emergency action when component failures occur—although some quite remarkable results have been achieved in this direction. At first a "shepherd" aircraft was used to "take-over" in case of emergency but this technique proved to be of little practical use and it was therefore abandoned when the crew gained confidence in the telemetry display and tracking aids.

TELEMETRY

Multiplexing and Accuracy

In most problems involving the telemetering of information, it is necessary to provide a means of handling a number of channels of information simultaneously, or nearly so, on a single radio communication link. The means by which this is done is called multiplexing. Frequency division multiplexing is the term applied to the process of dividing the bandwidth of the communication link into a number of discrete frequency bands, each band conveying a sub-carrier which may be modulated to provide an information channel. In time division multiplexing, a single carrier is allotted to the transmission of one of a number of channels of information for a certain time. Usually the sequence in which channels are sampled is repetitive, each cycle being identical; but there are cases when the sequence is a function of the information.

These are the two principal methods of multiplexing. Channels of a frequency division multiplex are continuous, and channels of a time division multiplex are essentially discontinuous. In the latter, however, provided the data is sampled sufficiently often, interpolation methods, either manual or automatic, can be used to "fill in" between samples and hence provide an effectively continuous channel. When a number of channels having a frequency response lower than that of the main channels of a multiplex are required, it is usual to sub-multiplex. Provided parameters are correctly chosen, it is possible to apply time division or frequency division multiplexing to an already multiplexed channel. The former is more common, and is usually referred to as sub-commutation.

The ground receiving equipment provides a means of displaying the output of each channel or recording it so that it can be analysed later, or both. In radio telemetry, noise in the radio link, principally receiver noise, limits the range over which the system can operate and this limit corresponds to what is usually termed the improvement threshold input signal level of the system. This threshold phenomenon is brought about by the manner in which detectors (a.m., f.m., etc.) in the receiving equipment function when an appreciable amount of noise is superimposed on the signal. Within this limiting range, for most types of telemetry, a proportion of the noise appears in the output of the channels, affecting system accuracy. The output data is usually filtered as much as possible, therefore, to reduce noise, but a short time delay is introduced. When the output data is recorded for subsequent analysis, this delay, although it may need to be known, is otherwise unimportant. When the display is required to represent the value of the data in "real" time, the delay must be treated as an additional error in the system.

The complexity and reliability of a telemetry system are largely determined by the type of multiplexing and number of channels used. Usually one of the difficult problems is to obtain stability in the modulators which code the information for transmission over the radio link, and sometimes in the demodulators. In frequency division multiplexing where each channel has its own modulator and demodulator, any instabilities appear as errors in transmitting the data. However, in time-division multiplexing, it is often possible to transmit known quantities through the system at selected intervals and hence to provide, in the receiving equipment, automatic means of compensating for instabilities. This technique is particularly applicable when the data to be transmitted is electrical in nature. Often it is required to telemeter, for example, a pressure or mechanical movement, which must be converted by means of a transducer to an electrical parameter before it can be telemetered. It is seldom that one can calibrate the entire telemetry system by feeding in known stimuli to every input channel.

One of the advantages of frequency division multiplexing is the ease with which one can provide a "real time" display of the output of each channel. The problem is somewhat greater with time-division multiplexing, particularly if sub-commutation is used, because of the necessity to synchronize the receiving equipment with the airborne multiplexer. However, this problem can be lessened considerably by using constant speed precision multiplexing switches now available from a number of sources.

Telemetry in JINDIVIK

The general requirements of telemetry in JINDIVIK, namely for control and for test flight, have already been mentioned. To avoid unnecessary development, existing systems were used: the RAE 6 channel telemetry(8,3) for control, and the RAE 24 channel subminiature telemetry(8,9) for test flights.

The RAE 6 channel system had been developed by Radio Department, RAE for flight testing of supersonic models(10). It was a frequency-division multiplexed system, utilizing audio frequency sub-carriers, an amplitude modulated carrier in the v.h.f. band (i.e. an f.m.–a.m. system), and having an output frequency response of up to approximately 100 c/s. To provide the facilities needed here, some modifications were required to the system constants, and to the input transducers and "real time" output display, but most of the original design remained unaltered.

Later, when it was decided to instrument JINDIVIK more fully for test flights, the RAE 24 channel subminiature (p.a.m.–p.f.m.–a.m.) telemetry system was used in addition to the 6 channel system. The 24 channel system had been developed for missile work by RAE Trials Department (then known as RAE Trials Division) and was already in regular use on the Woomera Range. It provides 24 data channels at a sampling rate of approximately 100 c/s using time-division multiplexing, and offers the essential facilities of viewing channels in "real time" and recording the data for subsequent analysis; furthermore the output data can be processed automatically.

Telemetry for Control (*The RAE* 6 *Channel Telemetry System*)

Airborne Equipment—The units comprising the airborne equipment are shown diagrammatically in Fig. 11. For channels 2–6 the information is converted first to movement, then to inductance change, and finally, by means of l.c. oscillators, to frequency modulation of sub-carriers. As the second process involves an approximate inverse square law and the next an inverse square root, the resulting sub-carrier frequency is nearly proportional to the movement. The sub-carrier for channel 1 is generated by a phonic wheel geared to the engine, and therefore its sub-carrier frequency is exactly proportional to engine speed. For channels 2–6 these processes correspond to the single function of the modulator, mentioned in the general discussion above, and therefore any instabilities in the transducers and oscillators appear as errors in the sub-carrier frequencies. The sub-carrier output of channel 1, on the other hand, is by design, a known function of engine speed and such errors do not arise. Finally, the six sub-carriers are linearly mixed at the input of a modulator unit which provides a means of anode modulating the crystal controlled v.h.f. transmitter. Transmitter output power is 5 W, and the signals are radiated

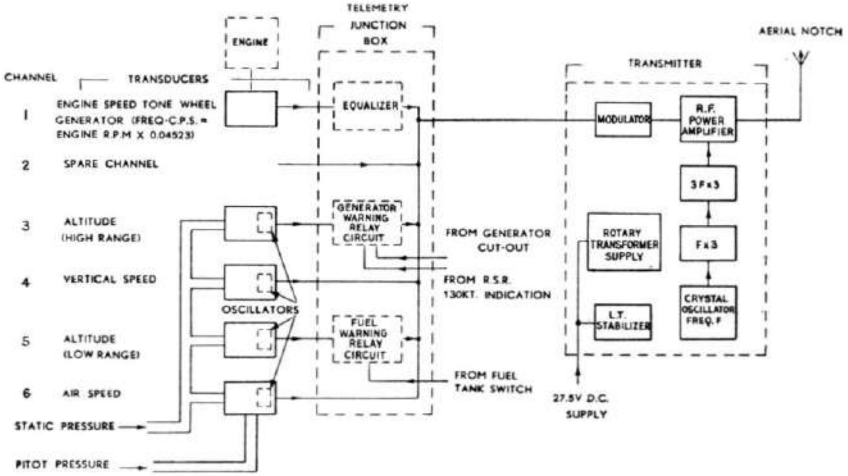

FIG. 11. JINDIVIK 6 channel airborne equipment.

from a notch aerial in the leading edge of the fin. The radiation pattern of the aerial is relatively free of nulls in the directions in which good transmission characteristics are required.

Receiving equipment—The receiving equipment is shown diagrammatically in Fig. 12. A simple vertically polarized receiving aerial is used to provide an omni-directional polar diagram in the horizontal plane. It feeds a conventional v.h.f. receiver, whose output is coupled via six band-pass filters to f.m. limiters and discriminators. The discriminators operate on the pulse averaging principle, the pulses being derived from r.c. differentiating circuits. The discriminator outputs are displayed in two sets of cirscale moving coil meters, one being a display for the control purposes and the other for the telemetry equipment operators. The outputs also

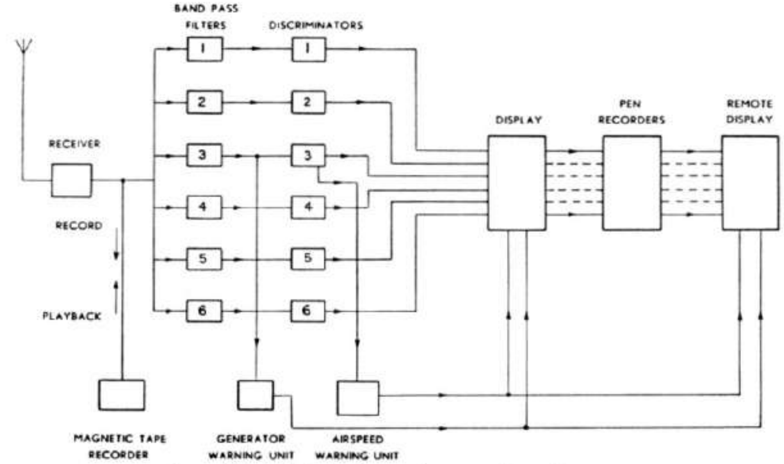

FIG. 12. RAE 6 channel ground equipment.

TABLE 2

Channel No.	Data telemetered (JINDIVIK)	Mean sub-carrier frequency c/s	Deviation c/s	Deviation % of mean sub-carrier	Bandwidth of sub-carrier c/s	R.M.S. noise % of full scale at threshold
1	Engine speed	373	237	63·5	670	0·019
2	Spare (various)	978	93	9·5	196	0·089
3	Altitude (high range)	1533	145	9·5	306	0·045
4	Vertical speed	2893	227	9·5	479	0·024
5	Altitude (low range)	3743	355	9·5	747	0·012
6	Indicated airspeed	5852	556	9·5	1172	0·006

actuate pen recorders. A magnetic tape recording of the "video" output of the receiver, and of other data associated with the flight (e.g. radio control signals) is made for possible analysis later.

Controlling parameters of the system—The channel parameters are shown in Table 2.

As is usual in this type of system, the sub-carrier amplitudes are tapered in proportion to the sub-carrier bandwidths so that all channels reach threshold at the same carrier input signal level to the receiver. The amount of noise in the output of each channel, expressed as a percentage of full-scale deflexion for various values of the carrier component of the input signal at the receiver, is shown in Fig. 13. The calculations have been based on the following typical conditions and follow the accepted procedure for an f.m.–a.m. system(11).

(i) Receiver noise factor = 10 dB
(ii) Carrier modulation depth = 60%
(iii) Equivalent noise bandwidth of display meters = 5 c/s
(iv) Carrier modulation improvement factor(11) = 1·2
(v) Aerial noise temperature = 300 °K.

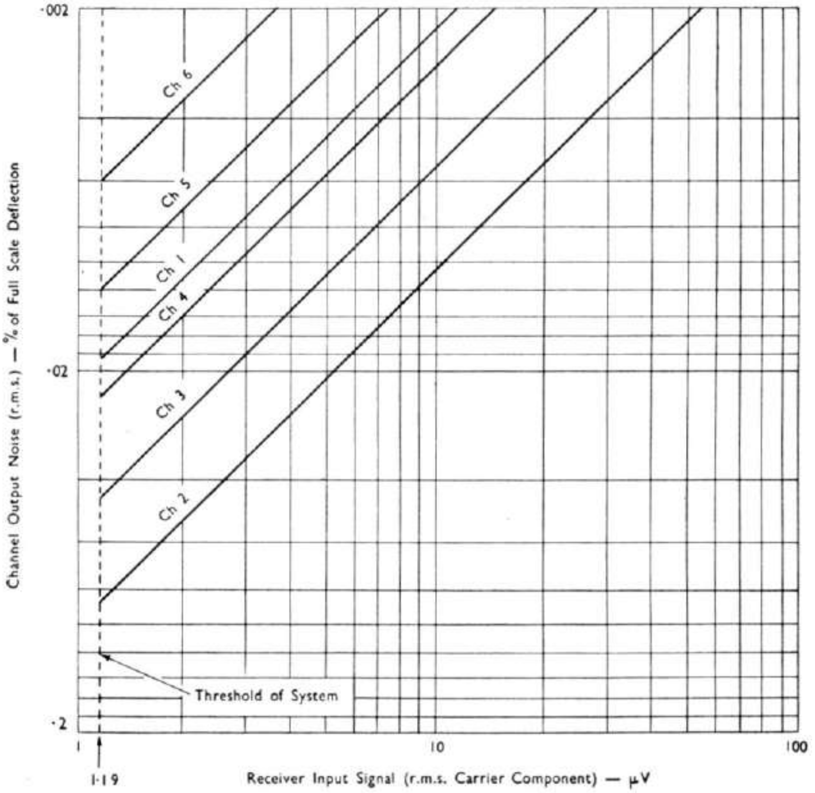

FIG. 13. Noise figures—6 channel system.

The amount of noise in the output is obviously much smaller than it need be; normally it is desirable to tolerate as much noise as possible in the interests of operating with the smallest possible input signal to the receiver. In this case, the use of display meters, having a low frequency response has resulted in this extremely small noise content, and consequently, the system is virtually noise free except when the input signal falls below the improvement threshold level (in practice approximately 1·5 μV). The noise then becomes excessive and the output data is useless.

The Application in JINDIVIK—The telemetry system is an essential aid for the satisfactory navigation of the aircraft to the exacting standards required for target use, and it is also essential for flight near the boundaries of performance or stability. It is not essential for cruising or, in fact, for landing and therefore the reliability required is not as high as that required of the control link or of the automatic controls. None the less, satisfactory cover is achieved over a range comparable to that of the radio control link. Some fades do occur at maximum range during turns and at high altitudes over-head, but these can be anticipated and are generally not troublesome.

Fortunately it is possible to obtain a basic check of both the low range altimeter and the airspeed channel before the landing phase. There is a contacting altimeter in the autopilot system which levels the aircraft automatically at 1500 ft from the descending condition. This function, easily recognized by the crew, provides a check on the altimeter reading, and further descents are then made with confidence. Similarly, a contacting airspeed instrument is available which provides a signal at 130 knots during the landing phase (via the out-of-scale high range altimeter channel) for the crew to check the accuracy of the airspeed information. In practice, the readings obtained are very accurate considering the simplicity of the system design, and it can be said that the crew trust the display and use it with much the same confidence as is placed in normal aircraft instruments.

Design Comments—From an accuracy point of view, the errors in the system originate mainly in the transducers and oscillators. The former are being used to the limit of their design; for example the airpseed is required to be known to 2% of the actual reading from 100 to 450 knots, and it would require a new design of transducer to obtain significantly better precision. The oscillators use directly heated valves and a subminiaturized form of construction. It is expected that with some re-design, improved performance could be obtained. Because of significant variations between transducer characteristics it has been found necessary to calibrate each transducer/oscillator combination separately, and to make individual cirscale meter display dials to suit.

It will be observed that the system as used in this application is rather wasteful of bandwidth. This, unfortunately, is the outcome of reducing the output bandwidth alone; had the sub-carrier frequencies also been reduced, some increase in range would have resulted, but this would have necessitated considerable re-design. Obviously, from the performance record of the system, such a refinement would not have been warranted.

Telemetry for Test Flights (The RAE 24 Channel Sub-miniature Telemetry)

Airborne Equipment—The airborne equipment is shown diagrammatically in Fig. 14. A mechanical switch is used to multiplex twenty-four data inputs, the multiplexed data then being fed directly to the modulator unit. One of the channels is adjusted to provide a unique output, and is used for synchronization of the receiving equipment. The mark/space ratio for each switch segment is approximately 10 to 1. The system can accept input data in the form of d.c. voltages and variable inductances, each inductance being tuned with a capacitor so that it resonates at a frequency within the normal sub-carrier frequency limits. The frequency modulator used in this application contains two oscillators, namely (i) a voltage controlled oscillator coupled to a balanced reactance valve circuit, and (ii) a transitron oscillator. Both oscillators have a common input terminal to enable the unit to be used with a single pole multiplexing switch, and they feed to a common output terminal. The input characteristics of the modulator are so arranged that the transitron oscillator is normally quiescent in the presence of a voltage input channel (provided its source impedance is low), and hence the unit behaves as a voltage controlled oscillator. Immediately the switch samples a tuned inductance, however, the transitron oscillator breaks into oscillation and overrides the control of the reactance circuit.

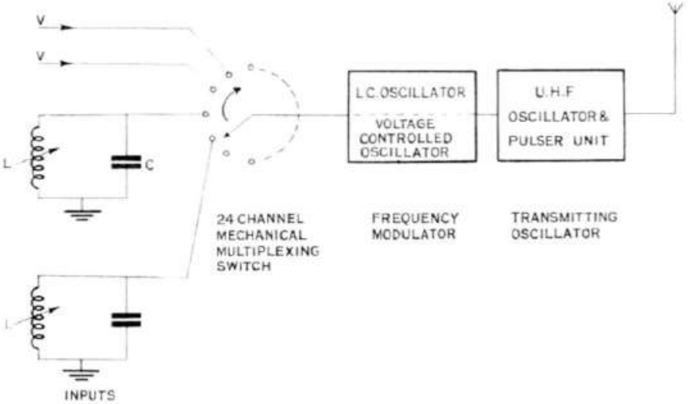

FIG. 14. RAE 24 channel airborne equipment.

The sinusoidal output of the frequency modulator is used to grid modulate the transmitter oscillator by means of a pulser unit, effectively converting the f.m. output of the modulator to pulse frequency modulation (p.f.m.). The signals are radiated via a unipole aerial mounted on the upper skin of the fuselage just ahead of the wing. The carrier frequency is in the u.h.f. band, the power output being approximately 7 W.

Receiving equipment—The receiving equipment is shown in schematic form in Fig. 15. In this particular application, a circularly polarized high gain receiving aerial is used. It is mounted on a tracking mount, and slaved to other tracking instruments, in order to follow the aircraft. The signals are received on a conventional u.h.f. receiver fitted with AGC, the i.f. bandwidth being 3 Mc/s. This wide bandwidth is advantageous in that appreciable oscillator drift can be tolerated. After limiting, signals pass to the f.m. discriminator, operating on the pulse averaging principle, in which constant area pulses are derived from a delay line and a constant current source. Four alternative output filters are provided to suit various sampling switch speeds.

The output data is recorded in four ways:

(a) Signals appearing at the input of the discriminator, while still in sub-carrier form, are translated in frequency to the band 35–85 kc/s and recorded on magnetic tape. This development was undertaken as part of a system for the automatic processing of telemetry data into the digital computer (WREDAC)*(12,13,14).

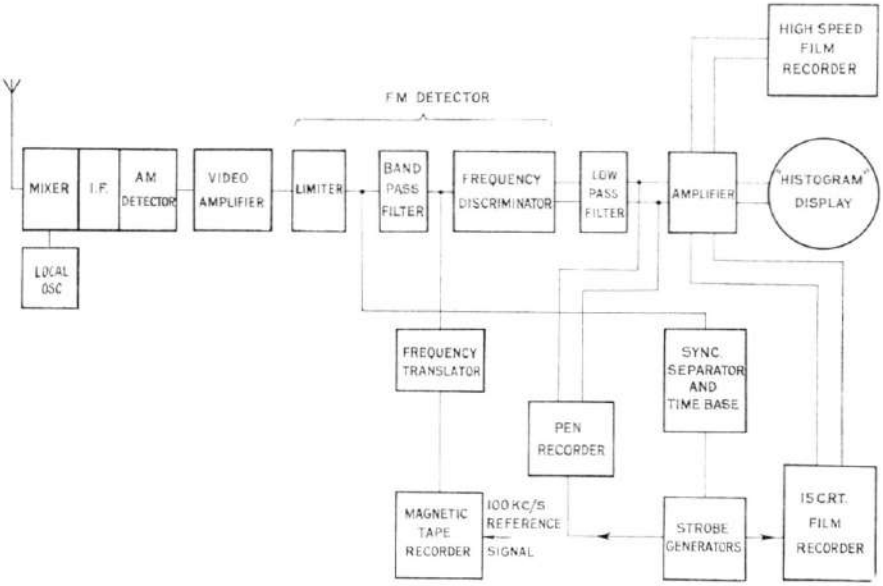

FIG. 15. RAE 24 channel ground equipment.

(b) Signals, consisting of the sequence of channel pulses (commonly called the "histogram") appearing at the output of the discriminator, are sometimes recorded on high speed film. This type of record does not depend on synchronizing the receiving equipment, and is therefore valuable in the event of a synchronization failure.

(c) The "histogram" signal is strobed, using pulses synchronized to the transmitted synchronization pulse, and the individual channel outputs are separated for recording on a bank of cathode-ray tubes.

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* Weapons Research Establishment digital automatic computer.

The photographic record of these traces (known as the "low speed" record), is very easily read, and, as it is possible to superimpose relevant calibration channels, the effect of drift in the telemetry system can be overcome by measuring relative to the calibrations.

(d) Selected channels, after having being strobed, are recorded using pens. This type of record is somewhat inaccurate, but it is useful for qualitative work, especially as it is immediately available.

Various "real-time" displays are available, but the most useful is a display of the "histogram". This has been used extensively by observers in the flight testing of JINDIVIK.

Parameters of the system—The more important parameters of the system are listed in Table 3.

TABLE 3

1. Data input for full scale deflexion	
voltage	0–+1·5 V
inductance	2–3 mH
2. Mean sub-carrier frequency	145 kc/s
3. Sub-carrier frequency deviation	±15 kc/s
4. Synchronizing pulse frequency	180 kc/s
5. Multiplexing switch speed	85–90 c/s
(note: other speeds may be used, but this is now the standard.)	
6. Receiver noise factor	13 dB (approximately)
7. Discriminator output bandwidth for condition 5 above (the equivalent noise bandwidth).	10·4 kc/s

The input signal required to reach the improvement threshold is at present about 7 μV in 50 Ω (carrier component only), and at this level, the r.m.s. noise in the output of the discriminator is 0·33% of full scale deflexion(15). Equipment will shortly be available, which reduces this input signal for threshold to approximately 1·5 μV.

Test Flights—Application of Telemetry—The RAE 24 channel system has proved to be an invaluable aid in investigating and controlling the performance of JINDIVIK as it is taken into previously unexplored conditions of flight. In one instance, certain flutter modes became prominent when wing tip pods (containing cameras) were fitted. To determine the safe maximum speed, a method was established of continuously assessing the damping of the vibration as speed was increased. Accelerometers were fitted in appropriate positions to detect the vibration and an excitation was applied, via the radio control link, at the discretion of the observer watching the telemetry display. A measure of the damping could readily be obtained by observing the amplitude and subsequent decay of vibration when the excitation was applied. By arranging for rapid deceleration on command it has been possible to fly very close to the onset of flutter without endangering the aircraft.

Similarly the system has been used in assessing the performance of the control system during the flight. All the gyro signals and the resulting control surface movements can be displayed very effectively on the ground and an observer can advise the crew when the limits of safe operation have been reached. A particularly troublesome long-period oscillation evident in high bank turns was tackled most successfully by this method.

Telemetry for this type of information has the additional advantage over the conventional airborne recorder that the results are available for analysis although the aircraft may be lost in the course of the test flight. In addition, as the recording is made on the ground and therefore the size of the recorder is not an important factor, the recording system can be chosen to minimize the subsequent data reduction required and so speed the analysis of the flight. This is quite an important feature when many instruments are monitored for a long flight. In this connexion the facility, whereby the output data can be fed to WREDAC for automatic reading and reduction, is extremely useful.

Although the system proved a valuable aid to test flights, further development would be required if it were to be used as a regular facility for monitoring. The fact that the airborne equipment cannot, as yet, operate conveniently with strain gauges or other millivolt input signals, is a handicap, and an improved aerial polar diagram would be desirable. On the receiving equipment side, further development of specialized displays would be needed to facilitate monitoring by operators not fully conversant with the "histogram" type of display, and to incorporate automatic drift correction.

RESULTS

Although we have relatively little knowledge of the results achieved with similar developments in other countries (apart from U.K.) it is considered that the record of reliability of the JINDIVIK MK. 2 would be reasonably representative of pilotless aircraft projects of this nature, using present day techniques. The following graphs indicate that we are quite a long way from approaching 100% reliability and (if the record can be regarded as typical) the day when the fully pilotless aircraft could be expected to appear in the spheres of transport or industry.

The records shown refer to the first 300 flights of the project except that flights resulting in destruction of the target by missile action have been excluded.

Flight Success Rate

Figure 16 curve A is a plot of unsuccessful flights against the total number of flights. For the purpose of this graph "success" is defined as achieving the main objective of the flight, i.e. that a satisfactory target was presented or that satisfactory records had been obtained from a test flight. All causes associated with the target flight are included, e.g. tracking

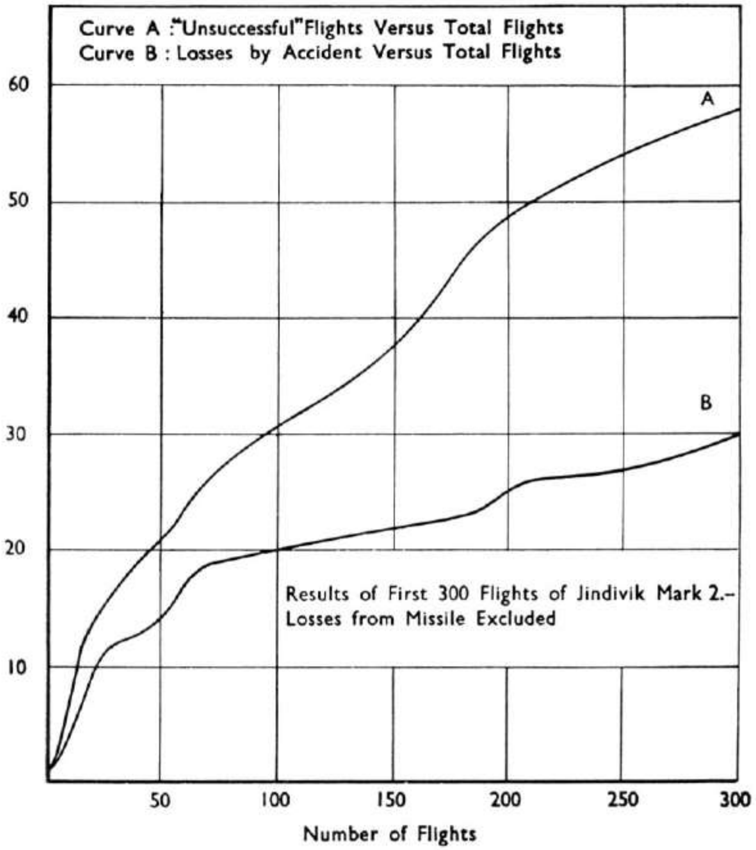

FIG. 16. Reliability record.

system faults, aircraft and control system faults, airborne instrumentation, etc. A steadily improving rate culminating in one unsuccessful flight in ten is evident.

Loss Rate

Figure 16 curve B is a plot of aircraft lost by accidents against the total number of flights. The slope of the curve is the loss rate. It will be seen that the rate gradually improved up to the seventy-fifth flight and subsequently an approximately constant figure of one aircraft lost in twenty flights has been maintained.

Failure Record: (Failure of System Components)

Figure 17 shows the number of failures, resulting in loss of the aircraft, which have been attributed to failure of the various components of the aircraft or to operating faults.

It will be appreciated that the losses from early development trials are included and that therefore some of the failures shown can be attributed

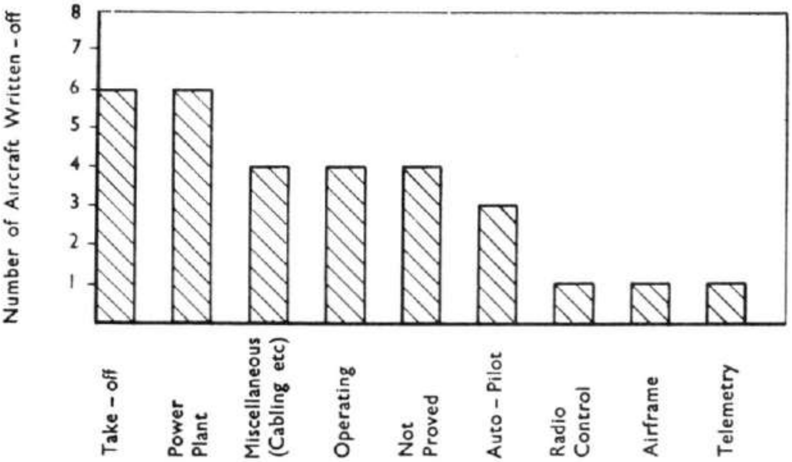

FIG. 17. Failure of components.

to design difficulties which have been overcome with experience. The relative proportions attributable to these factors are changing with time because of the introduction of design improvements.

FUTURE TRENDS

The following remarks indicate the trend that is being followed in the application of the telecommand and telemetry equipment to the JINDIVIK MK. 3, which is being developed to give a higher performance than JINDIVIK MK. 2.

Reliability

In order to provide a sufficiently reliable target service for missile trials it has been found that standards of design and workmanship should be generally equivalent to those employed for normal aircraft and that the natural tendency to lower the standard because of the expendable rôle of the aircraft should be regarded as false economy when considered as part of the operation of the Range as a whole. Looking back on the results for examples, the original decision to use a short-life engine for economy reasons now seems unwise, and the aim of achieving reliability in take-off by means of using a simple system, was not achieved.

Apart from these two examples it is considered that the remainder of the system has functioned with reasonable reliability and that no great improvement can be expected without (i) extensive re-design for the inclusion of many redundant components (e.g. carrying a spare automatic pilot, etc.) or (ii) the inclusion of improved monitoring facilities to warn the crew of impending failures.

At the beginning of the JINDIVIK programme it was envisaged that, in the interests of efficiency, automatic controls should be extended to cover almost every aspect of the flight so reducing the responsibility of the crew and possibly eliminating the need for the cockpit telemetry display (which was regarded with suspicion). However, because of the high standard of reliability reached with the telemetry systems, the relative costs involved and the flexibility offered, more extensive manual control and more monitoring is now favoured. It is intended that the "skipper" of future targets will have more information and more controls at his command, and that his crew will include a flight engineer with similar responsibilities to those of his counterpart in the crew of a large piloted aircraft.

On the other hand, in keeping with the principle that airborne equipment should be simple but ground equipment may be complex, it is intended to duplicate some of the take-off system components to improve reliability and reduce the loss rate from this cause.

Development Techniques

As previously discussed, the experimental method has been used almost exclusively in the development of the control technique for the JINDIVIK aircraft and by a gradual process the difficulties were isolated and overcome. More recently we have had access to analogue computers and from brief experience so far it is apparent that very much more progress can now be made in the analytical stage by making full use of these machines, and that flight testing can be reduced by a very large factor. For this purpose it is desirable also to measure a very large number of parameters on each test flight. For the current development flight programme, based on prior simulation of the problem, 48 information channels (two 24 channel telemeters) are being used in addition to the normal cockpit telemetry display. The work in establishing the analogue, and the cost involved, can be readily justified by the saving in flight trials of the pilotless aircraft.

Telemetry

Steps are already being taken in U.K. to increase the number of channels of the RAE 6 channel system by the addition of another sub-carrier, time multiplexed to provide 24 channels at a low sampling rate. The accuracy is not expected to be high at first and there will be some loss in range; however, the extra channels are expected to fill an immediate need for more flight information, and will probably suffice for some aspects of test flights. WRE is engaged on developing the associated equipment to utilize these channels.

On a long term basis a reliable and flexible telemetry system is needed. It should include the following main features:*

A. Provide channels on the following basis:
   (i) For routine monitoring and telecommand
      (a) Ten channels, 0 to 0·1 c/s for function monitoring.

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[*] Compare with conclusions for piloted aircraft testing, Ref. 16.

  - (b) Twenty channels, 0–2 c/s, for flight parameters (to cover short period modes and for response compatible with reaction time).
- (ii) For test flights an information bandwidth of approximately 200 c/s for flexible use to cover different experiments, e.g. 3 channels (0–15 c/s) for autopilot functions (to cover rate gyro and antivibration mount resonances), and 3 channels (0–50 c/s) for aircraft vibration (to cover the highest flutter frequency).

B. Basic system accuracy, excluding transducers, should be approximately ¼% (r.m.s. noise/f.s.d.).

C. The system should be designed to operate with voltage (including the millivolt output of thermocouples) and strain gauge outputs.

D. Time-division multiplexing should be used as the most practical means of obtaining the flexibility and self-calibrating features considered desirable. The required commutation rate should be calculated on the basis of 5–6 points per cycle.

E. As the information bandwidth is relatively small, the design can be chosen primarily to obtain a high reliability. Thus it would be desirable to use redundancy wherever appropriate (e.g. diversity transmission, self-checking synchronization).

F. Adequate provision for displaying the output data accurately in "real-time" should be provided and data recording should be compatible with the input requirements of digital and analogue computers.

ACKNOWLEDGEMENTS

The original design of most of the telecommand and telemetry equipment described in this paper was carried out in the United Kingdom under the direction of scientists of the Royal Aircraft Establishment, with some Australian participation, and helpful advice was given by the designers in the application of the equipment in Australia.

The Jindivik aircraft is designed and produced at the Government Aircraft Factories, Melbourne. The development in Australia has been a joint effort between GAF, WRE, Aeronautical Research Laboratories, Melbourne, and the Royal Australian Air Force.

The authors are grateful to the staff of Target Aircraft Group and others in the Weapons Research Establishment, for many helpful suggestions particularly Mr. B. S. Deegan who has contributed most helpfully to the section on telemetry.

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APPENDIX

Jindivik Automatic Pilot Equations

Pitch Channel:

"Chocks-away" to 130 knots

$$\eta = (k_1 p + k_2)\,\theta + \text{take-off transient} \qquad (1)$$
$$k_1 = 0{\cdot}73,\ k_2 = 0{\cdot}61$$

Non-level flight

$$\eta = (k_1 p + k_2 + k_3 p^{-1})\,\theta + \text{flap transient} \qquad (2)$$
$$k_1 = 0{\cdot}29,\ k_2 = 0{\cdot}58,\ k_3 = 0{\cdot}054$$

Level-flight

$$\eta = (k_1 p + k_2)\,\theta + (k_3 + k_4 p^{-1})\,\frac{h}{\sigma} + \text{flap transient} \qquad (3)$$
$$k_1 = 0{\cdot}29,\ k_2 = 0{\cdot}58,\ k_3 = 1{\cdot}2,\ k_4 = 0{\cdot}042$$

Roll and Yaw Channel:

"Chocks-away" to 130 knots

$$\xi = (k_1 p + k_2)\,\phi \qquad (4)$$
$$k_1 = 0{\cdot}21,\ k_2 = 0{\cdot}37$$

Straight flight

$$\xi = (k_1 p + k_2)\,\phi + (k_3 p + k_4 + k_5 p^{-1})\,\Psi \qquad (5)$$
$$k_1 = 0{\cdot}21,\ k_2 = 0{\cdot}37,\ k_3 = 0{\cdot}17$$
$$k_4 = 0{\cdot}36,\ k_5 = 0{\cdot}01$$

Turning flight

$$\xi = (k_1 p + k_2)\,\phi + k_3 \frac{h}{\sigma} + \text{Constant} \qquad (6)$$
$$k_1 = 0{\cdot}21,\ k_2 = 0{\cdot}37,\ k_3 = 0{\cdot}35 \text{ (level flight only)}$$

Transients and Constant

Take-off transient applied at 110 knots ($t = 0$)

$\eta = 12^\circ\, e^{-t/10}$ see equation (1)

Flap transient applied when flaps are lowered ($t = 0$) or removed when flaps retracted.

$\eta = 1^\circ + 3^\circ (1 - e^{-t/10})$ see equations (2) and (3)

Constant in turning flight is value of

$\xi = k_5 p^{-1}\, \Psi$ see equation (6)

applying when the turn is selected.

SERVO RESPONSE:

No allowance has been made for the control surface servo response time in the above equations. This is significant when considering short transients or the short-period stability. The following average equation can be applied for small elevator or aileron angles.

$$\text{Movement} = \frac{\text{demand}}{1 + 0{\cdot}4p + 0{\cdot}006p^2} \tag{7}$$

Limits of Demand

Pitch platform	$\pm 30^\circ$ at 4°/sec
Roll platform	$\pm 60^\circ$ at 10°/sec
Fine turns (heading)	$\pm 10^\circ$ in $\frac{1}{2}^\circ$ steps

Nomenclature

η = Elevator angle
ξ = Aileron angle
θ = Attitude error
ϕ = Bank angle error
Ψ = Yaw angle error
h = Height error*
σ = Relative air density
t = Time in seconds
e = Base of the natural logarithm
p = Differential operator

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* The height error h is expressed in 50 ft units at sea-level (ICAN scale) when the angles are expressed in degrees.