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COMPATIBILITY OF INFORMATION AND MODE OF CONTROL: THE CASE FOR NATURAL CONTROL SYSTEMS

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The operation of control systems has been determined largely by mechanical constraints. Compatibility with the characteristics of the operator is a secondary consideration, with the result that control may never be optimal, control workload may interfere with performance of secondary tasks, and learning may be more difficult and protracted than necessary. With the introduction of a computer in the control loop, the mode of operation can be adapted to the operator, rather than vice versa. The concept of **natural control** is introduced to describe a system that supports control of the information used by the operator in achieving an intended goal. As an example, control of speed during simulated approach to a pad by helicopter pilots is used to contrast path-speed control with direct control of global optical flow-pattern information. Differences are evidenced in the performance domains of control activity, speed, and global optical flow velocity.

"Smart" mechanisms for perception and control. It might be supposed that other flying animals have "smart" perceptual mechanisms (Runeson, 1977) for acquiring information that maps directly onto an action system specialized for controlling flight. In contrast, human flight must be mediated by a vehicle. Whereas the human's perceptual mechanisms may be sufficiently smart to pick up the relevant information, manipulation of the control surfaces is apt to be quite foreign to an animal whose effectivities (ways of being effective) and prior experiences involve adaptation to terrestrial locomotion. Smart action systems can evolve to support flight control by other flying animals, but for human control of flight they must be developed and tested. The flight environment demands that the principles be the same.

Accordingly, human guidance of flight can be described (a) in terms of the manipulation of controls, control surfaces, and power, (b) control of the path, speed, and orientation of the aircraft, or (c) control of the information which specifies where one is headed, at what speed and orientation, and the consequences of continuing without change. The last description has advantages for the development and evaluation of control systems because it keeps the variables to which the pilot is sensitive and the variables to be controlled in the same currency, i.e., in the domain of visual information. In performing a maneuver, the pilot cycles between sampling the information available and performing control adjustments to reduce deviations from desired optical conditions, repeating the perception-action cycle until satisfactory visual conditions have been achieved. As a consequence, the information acquired by perceiving and the information controlled by acting must be the same. The compatibility between control adjustments and visual guidance of flight could be maximized by giving the pilot direct control of the informative variables.

The nature of information to be controlled. A canonical assumption of the direct theory of visual perception (Gibson, 1979) is that detection and control of any property of self motion must be supported by information. This holds for selecting and modulating a control action, timing the initiation and termination of the action, and observing the consequences of the action. In the case of visual guidance, the information is assumed to be one or more invariants in the surrounding, transforming optic array along the path of motion. Applications have been extended to rotocraft flight (Owen, 1991), simulation research (Owen & Johnson, 1992; Warren & Owen, 1982), and transfer of training (Lintern (1991).

The research approach first isolates variables in the optic array between the eye and environmental surfaces mathematically and operationally (through manipulation of scene-content and flight parameters). Second, experiments are conducted to determine which of the potential sources of visual information are functional, i.e., useful for detecting changes in speed and direction and for selecting and guiding a control action. To date, functional variables have been exclusively fractional rates of change characterized by higher-order ratios of such lower-order variables as speed, acceleration, altitude, climb or sink rate, and ground-texture-element size and spacing. The **eyeheight** of the observer above the ground is an optically privileged scaler for size, distance, and speed, and therefore fundamental to the perception and control of visual information. See Owen & Warren (1987) and Owen (1990) for summaries of the experiments.

Control of optical variables. If the criterion for skillful behavior is taken to be effective **control** of the informative structure of stimulation, then its study requires an **active** psychophysics that treats transformations and invariants in the ambient array as **dependent** variables (Owen & Warren, 1982; Warren & McMillan, 1984; Flach, 1990). Controlling self motion involves maintaining intended conditions of speed and direction of flight, as well as self orientation, relative to environmental surfaces. In the process, variables are linked and unlinked as speed, direction, and orientation change. With knowledge of the relevance of the different kinds of information to different kinds of flight tasks, the variables and their linkages can be controlled to achieve intended goals. The same ambient array properties which were independent variables in passive judgment experiments can be recorded as dependent variables in the study of active control.

Direct or natural control. Using the cyclic and collective, helicopter pilots currently make an average of 50 control adjustments per minute during an approach to hover above a place on the ground. Pilots are instructed to keep "visual streaming" constant at the rate of a brisk walk during an approach to hover. Control systems for helicopters and other aircraft have been designed primarily around mechanical constraints, including those of cables, levers, and hydraulic systems. The development of electronic and optical systems communicating between controls and control subsystems, including power, allows for the implementation of "smart" control systems designed to provide a match between the sensitivity of the human perceptual system and the effectivities of the human-vehicle action system. Thus, a computer in the control loop can allow a hybrid between manual and supervisory control: The pilot maintains higher-order control (e.g., over path slope), while the computer manages the lower-order control tasks (power, rotor variables).

The logic is similar to that employed by Roscoe and Bergman (1980) in developing a control system that reduced higher-order control loops for bank angle and vertical velocity to first-order control of heading and vertical position (altitude). Compared to normal flight control, their system reduced pilot errors by a factor of ten. Ratio control differs in providing direct control of the higher-order variables to which the pilot is sensitive. (A simple example is the Vernier log scale for acoustic volume control.) The computer can take inputs from the controls and sensors (e.g., radar altimeter, forward-looking radar, a signal transmitted from the ground or a ship) and make adjustments in speed and direction to match the informational properties of the event that the pilot intended to produce. For approach to the ground or to surfaces with vertical extent, a fractional rate controller can reduce speed in the same proportion as distance to the surface is decreased. The pilot selects a fractional rate which matches the task demands, e.g., a high rate when time is critical, a low rate when accuracy is important. A second mode of control is appropriate for path angle. Whereas magnitude controllers vary the numerator or denominator of the ratio of vertical speed to ground speed, a path-slope controller varies the ratio directly. Since path slope equals the "dip" angle of the point of optical expansion below the horizon, the path-slope controller gives the pilot control over what he intends to achieve visually. Similar ratio modes could be developed for rotational control.

<u>Advantages of natural control.</u> A control system designed around perception-action compatibility should reduce flight-control demands, freeing the pilot's attention for other workload. Maneuvers under difficult conditions should be simplified. Given that control is scaled in units of distance to the ground, fractional-rate control is particularly appropriate to approach, hover, and low-level contour and terrain following. Modes of control compatible with information acquisition should greatly simplify training and increase safety at low altitudes in cluttered environments and under difficult conditions, e.g., high work load or stress. Although experienced helicopter pilots have shown no sign of negative transfer when using ratio controllers, having a computer in the control loop means that traditional modes of control could be programmed and selected, if desired, by a pilot more comfortable with those modes.

A design criterion for some new aircraft is that "trainability" be taken into account during development of the aircraft itself. Ratio controllers are relevant to this criterion, since training should be considerably simplified with a high compatibility system having independent modes of control, as compared to the current system involving complicated and sometimes arbitrary relationships between control adjustments and visual stimulation as well as interdependent relationships between the controls themselves. Lintern (1991) has discussed the role of optical information in manual control and transfer of training.

Kurlik (1991) proposed that experts make a task easier because they constrain the task in ways that make the variables controlled much simpler to skillfully control. One reason that the novice may have difficulty learning what to attend to and control is that information **emerges** during an event. The information which the skilled pilot uses to select, initiate, and terminate control actions may not come into existence until the environment is **skillfully** controlled (Kurlik, 1991). Ratio controllers should give novices an advantage in that they automatically isolate task-relevant optical variables that are transforming in a specificity relationship with the flight event. In this way, they embed a dimension of skillful performance in the control system itself. Automatic braking systems on automobiles perform a similar function by pulsing the brakes in an optimal fashion to achieve deceleration while avoiding locking up the wheels. Braking performance of a novice driver using the automatic pulsing system should be better than without it, even though the driver is unaware of the mode of operation. Just as information is ordinarily transparent to the perceiver of an event, the means by which control of an event is achieved via the direct control of information can be transparent to the controller of the event. The test is whether direct control of the variable an operator is sensitive to results in better performance than control of a task-relevant property of the self-motion event itself.

Experimental tests. Two experiments will be used to illustrate direct control of optical flow-pattern information. Experienced pilots with an average of 1,500 hours helicopter flight time participated. In the first experiment, each pilot controlled speed for 25 seconds during 136 simulated approaches to a pad along a linear flight path. In one session the pilot controlled path speed, and in the other he controlled global optical flow velocity (path speed/ eyeheight). The approaches were made in 68 different environments designed to determine the relative influences of flow velocity and edge rate on speed control. In the second experiment, each pilot controlled vertical speed on a vertical path to maintain hover at 10 meters for 30 seconds, then descended to the ground while attempting to minimize vertical speed at touchdown. A total of 54 events were produced by combinations of disturbances in the three translational axes crossed with environments that isolated three types of information for change in altitude: change in the horizon ratio of a vertical surface, change in perspective angle of runway edges perpendicular to the horizon, and optical expansion and contraction of fields running parallel to the horizon. In one session, the pilot controlled path speed (sink and climb rate) and in the other he controlled global optical flow velocity (vertical speed/eyeheight, or fractional change in altitude). Comparisons of the two control modes were made in three performance domains: control activity, speed, and global optical flow velocity.

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