ANALOG COMPUTER PROGRAMMING OF HOVERING VTOL DYNAMICS PART 2: EXPERIMENTAL MECHANISMS AND COMMENTS ON MANUAL CONTROL

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Introductory Analog Simulations

We begin with the two-dimensional hovering task of a hypothetical VTOL vehicle having one or more powerplants generating a resultant normal fixed thrust force T_R so that the vehicle hovers in reference to a ground plane at a specific attitude. The vehicle is controlled by a translational control technique in which a specific body attitude results in a translational motion. Motion along the X-path (back/forth) is achieved by introducing control input δ_θ that makes the vehicle rotate by a pitch angle θ, thus tilting the (fixed) thrust T_R which resolves into a horizontal component T_H and a vertical component T_V.

We let $K_{\delta\theta} = M_{\delta q}/I_{yy}$, the pitch control sensitivity, $K_{\delta\varphi} = M_{\delta p}/I_{xx}$, the roll control sensitivity, and $K_\varphi = K_\theta = g/m$. Then, the two-dimensional hovering transition problem (for small angles) is described by the following two systems of equations.

$$\ddot{\theta} = K_{\delta_\theta}\delta_\theta \tag{19a}$$

$$\ddot{x} = K_\theta\,\theta \tag{19b}$$

And

$$\ddot{\varphi} = K_{\delta_\varphi}\,\delta_\varphi \tag{20a}$$

$$\ddot{y} = K_\varphi\,\varphi \tag{20b}$$

Therefore, the transfer functions of the system are:

$$\frac{X(s)}{\delta_\theta(s)} = \frac{K_{\delta_\theta}K_\theta}{s^4} \tag{21}$$

$$\frac{Y(s)}{\delta_\varphi(s)} = \frac{K_{\delta_\varphi}K_\varphi}{s^4} \tag{22}$$

Figure 1 shows the analog mechanizations of the system. As is, the vehicle is a pilot's nightmare. It is impossible to fly it, because control inputs result in continuously growing departures. The departure mechanism must be understood because it exists, at least in part, in most VTOL situations. An input step function integrated once results in a linear ramp during the duration of the input (constant rate while input is present), followed by constant position when the input zeros. Integrated twice, the input step function results in a quadratic increase (constant acceleration) for the duration of the step, and a linear increase (constant rate) when the input zeros. An input integrated three times results in a cubic increase (constant rate of the rate of change of acceleration, that is, constant jerk), followed by a quadratic increase (constant acceleration) when the input zeros. The fourth generation implies that control input must be the fourth derivative of the output; thus, we are asking the controller to perform the impossible task of generating the fourth derivative of an infinite-amplitude signal. This was the case in some early "flying platform" experiments in which a person was situated on a powered-fan platform, tempting fate by using body weight shift for tilt control in both axes (see,[10,29,30,31]). From a transfer function perspective, the system has a fourth-order pole at s = 0 (Equations 21 and 22), where the four cascaded integrators make the denominator vanish. As a result, any input excitation (controller action, noise, or both) induces a continuously growing response in output (see [1], on the stabilization of an unstable plant and [16] pp.278-280). We strongly recommend the excellent article[20].

Ideally, a specific control input induces a specific body attitude which, in turn, causes a specific translational motion.[18,23] The translational motion must be arrestable by merely neutralizing the control—a temporary control input should not result in a continuous departure (read also [35]). Here, we will make an attempt to alter vehicle instability by altering the dynamics of the system itself. We wish to modify the natural frequencies of the system so its response time will change and reduce the sensitivity to both controller and ambient noise inputs. Negative feedback comes to mind, so we add the two feedback loops shown in Figure 2. The system's new transfer functions are:

$$\frac{X(s)}{\delta_\theta(s)} = \frac{K_{\delta_\theta} K_\theta}{s^2\left(s^2 + a\,s + b\,K_\theta\right)} \qquad (23)$$

$$\frac{Y(s)}{\delta_\varphi(s)} = \frac{K_{\delta_\varphi} K_\varphi}{s^2\left(s^2 + c\,s + d\,K_\varphi\right)} \qquad (24)$$

according to the block diagram development shown in Figure 3. The system has four natural frequencies: two equaling zero, the values for the other two depending on the parameters (a,b) or (c,d). The vehicle no longer exhibits constant departure responses but a manageable exponential decay response. There are, of course, many more ways to improve our aircraft. The beauty of the process includes the apparent absence of limitations as to our creativity, the benchtop testing of our ideas as they occur, and the synthesis of the many techniques involved.

An important issue is the choice of variables to be monitored by the pilot. In experiment design this can be a source of trouble. Working with dφ/dt and dθ/dt gives a phase lead of 270º, monitoring d^2y/dt^2 or d^2x/dt^2 gives 180º of phase lead, and signals dy/dt or dx/dt provide 90º of phase lead. There are also the angular displacement (φ,θ) and the lateral and longitudinal position signals (y,x). Mixing approximately weighted and well-chosen signals in a single display appears to be the best solution. This, however, is another long story.

A Final Analog Simulation

The third and final analog computer program is structured according to the equations by McLean and Naseem[24] used in the investigation of a simple sub-optimal on/off flight controller for a VTOL aircraft (see also [11] for work on the effect of stabilization on VTOL aircraft hovering flight). Equations (16), (17), and (18) from part 1 of this paper are simplified and modified by letting the inertia terms I_{xx}:I_{yy}:I_{zz} = 1:2:3, which cleverly reduces two inertia term coefficients to unity, leaving the third term $[(I_{yy}-I_{xx})/I_{zz}]$ = 0.333. The stability derivatives are:

$L_{\delta p}/I_{xx} = 0.2$	$L_p/I_{xx} = -2.8$
$M_{\delta q}/I_{yy} = 0.2$	$M_q/I_{yy} = -2.8$
$N_{\delta r}/I_{zz} = 0.539$	$N_r/I_{zz} = -0.656$
$L_\varphi/I_{xx} = -4.0$	$M_\theta/I_{yy} = -4.0$

These are somewhat arbitrary values, as our research shows wide variations depending upon vehicle type.

The block diagram of Figure 4 shows the dynamic structure of the simulated vehicle. Note that the negative derivative signs have been transferred to the respective feedback paths, clearly showing the negative feedback closures of the system, previously identified as damping gains and attitude feedback gains. We consider the block diagram a valuable tool in visualizing the dynamic structure of the system. The analog computer program of Figure 5 follows. Our analog computer breadboarding uses both inverting and noninverting units in a sensible way. We first prepare a block diagram of the system to be simulated. We invert only when necessary. We use summing amplifiers instead of summing at the integrator input (so that acceleration signals are observable, recordable, and available during an experiment). Integrators are noninverting and buffers are used liberally for impedance isolation. (High quality operational amplifiers are very inexpensive.) A unique feature of the equipment is that loop gains are set by electronic (inverting or noninverting) amplifier units rather than potentiometers; the later are used only when we are certain that fractional gains is all we will ever need. We use operational amplifier circuits designed to perform accurate linear and nonlinear computations in conjunction with multipliers and multifunction integrated circuits. We have found that scaling is not a problem at the typically low frequencies found in man-machine experiments. High-speed repetitive operations are neither necessary nor desirable to our experiments.

Epilog—So Why Simulate VTOL Aircraft ?

In recent years there has been a slow but visible movement toward designing a practical "people's" VTOL machine. A VTOL flying platform can be a manned vehicle of high utility in many areas. It is also suitable for airborne robotic and remotely-piloted vehicle (RPV) applications. There exists an immense body of technical information on VTOL aircraft which, however, is very difficult to find—inaccessible to the average worker who often tends to reinvent the wheel. We believe that "old" technology should be reexamined, rekindled, and reapplied with modern materials, electronics, control systems, etc. The parallel use of simulation and flight testing with properly scaled models can solve most problems inexpensively. Simulation, data fitting, and dynamic model-matching techniques based on valid mathematical models yield valuable information on the dynamic structures themselves. They serve to uncover and illuminate normally imperceptible issues of system behavior, the cross-coupling and sensitivity of variables, etc.

Fortunately, NACA/NASA has conducted a lot of research on VTOL aircraft, lift mechanisms, simulation, etc. Their publications along with the British ARC and NATO AGARD report constitute virtually the entire body of "findable" VTOL research documents (in addition to those found in technical journals) in the English language. One may begin with Kuhn's review of basic VTOL aerodynamics[17], followed by Hill's fundamentals for efficient hover control [12], Reeder's review on handling qualities [33], Lollar's note on VTOL handling qualities criteria[19], Miller's work on the presentation of handling qualities criteria of unstable systems [25-27], and Rotrel's report on VTOL handling qualities[34]. Rampy's work on the stability derivatives in hover and transition[32] is also recommended here. While our paper deals with hovering only, a thorough VTOL study should investigate the critical transition regime also. In summary, VTOL simulation examples are found in James et al.[15], Isakson and Buning[14], Faye[4], Garren and Assadourian[7], Gerdes and Weick[8], Franke and Döpner[5], Holden [13], McIntyre[22], Castle and McIntyre[2], Goldberger[9], Streiff[37], Sinacori[36], Fry et al.[6], Greif et al.[11], McLean and Naseem [24], Corliss et al.[3], and Oesterlin[28].

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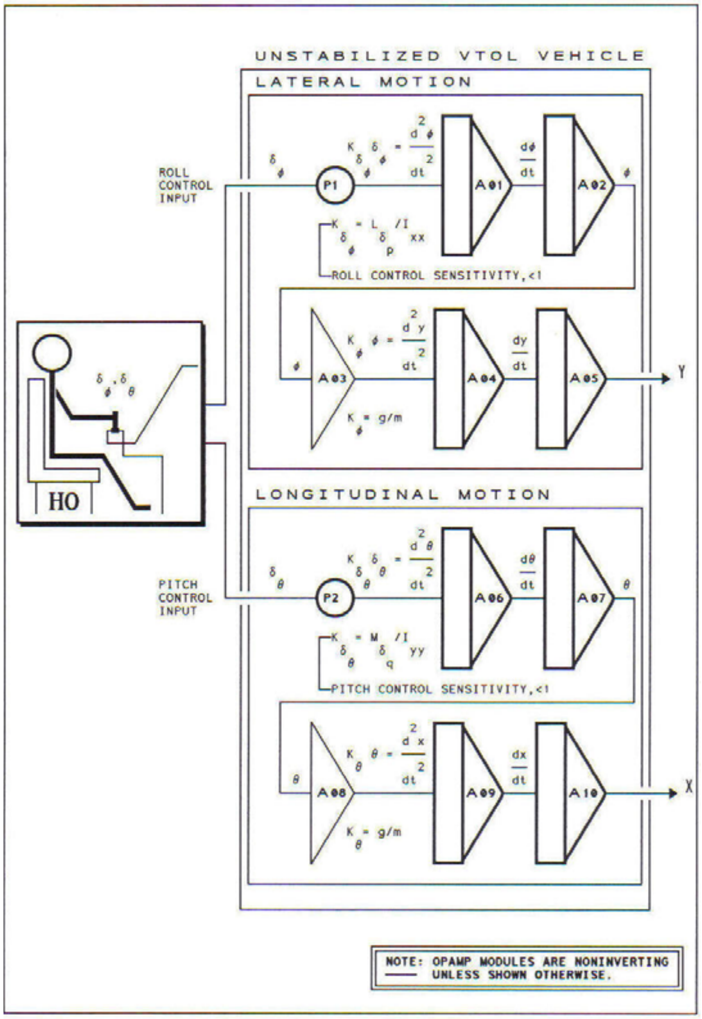

Figure 1 Simulation setup for the fundamental VTOL control task.

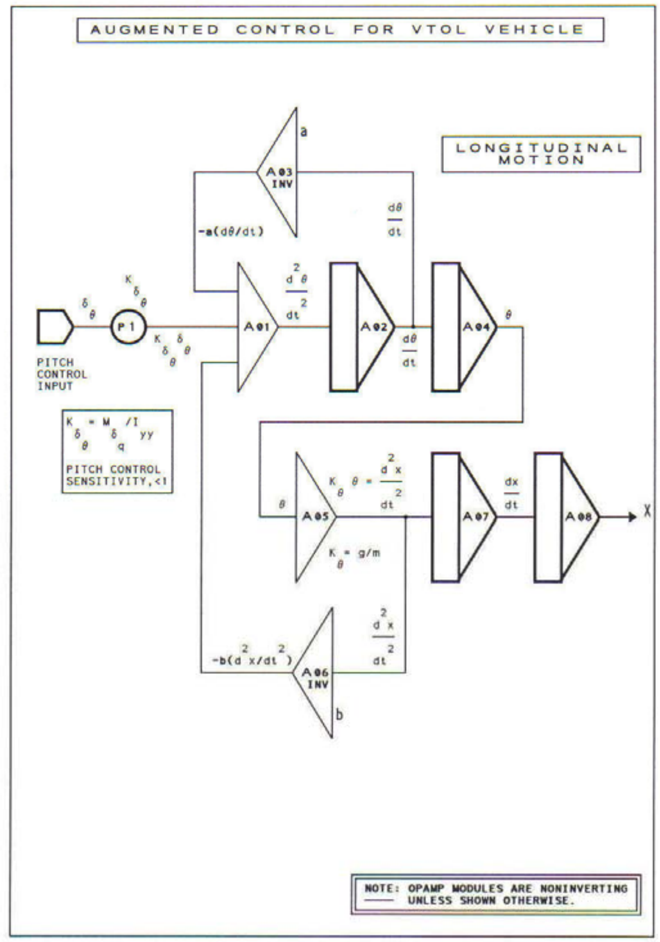

Figure 2 Improving VTOL vehicle dynamics with negative feedback (one axis shown).

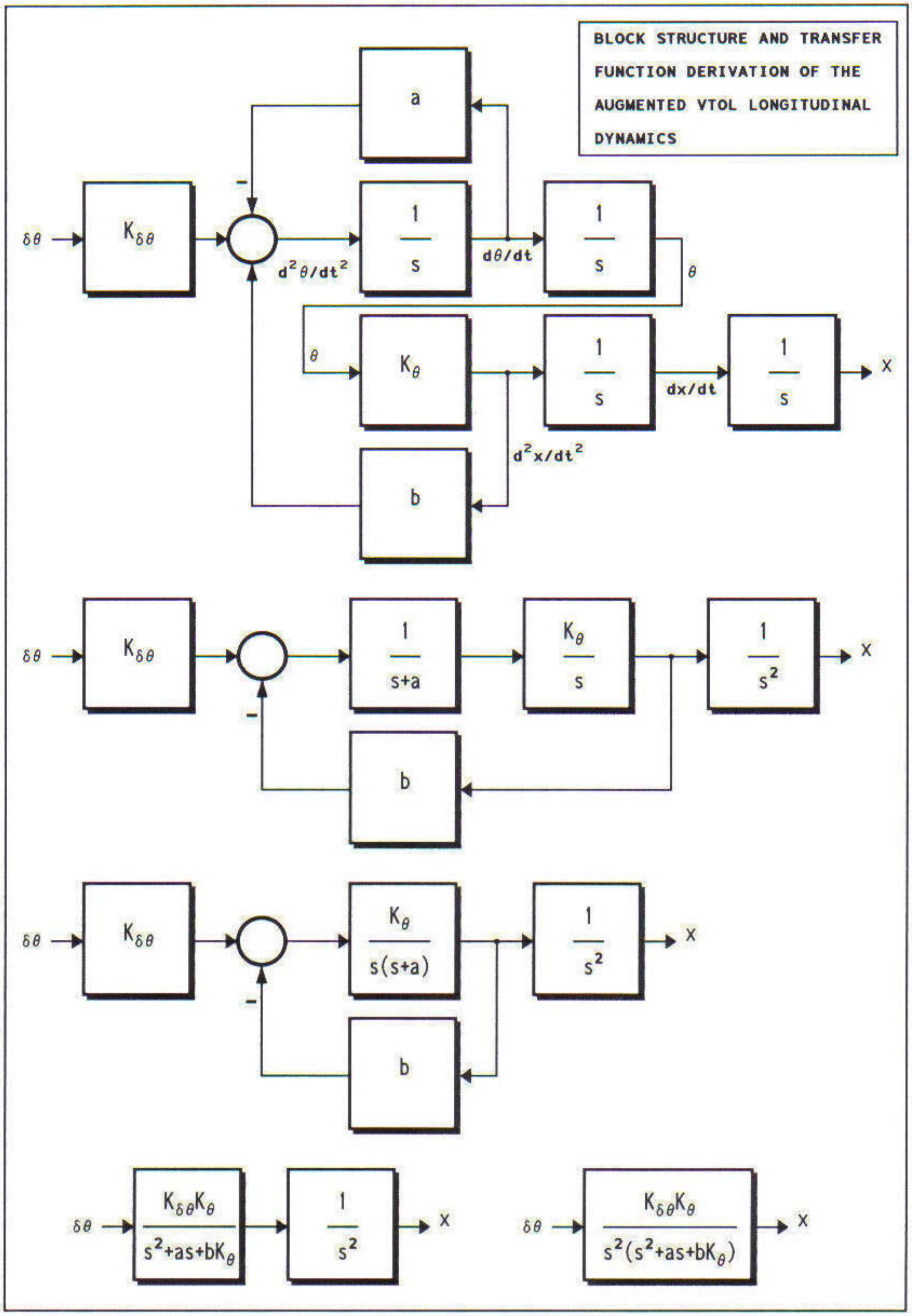

Figure 3 Developing the transfer function of the augmented VTOL longitudinal dynamics.

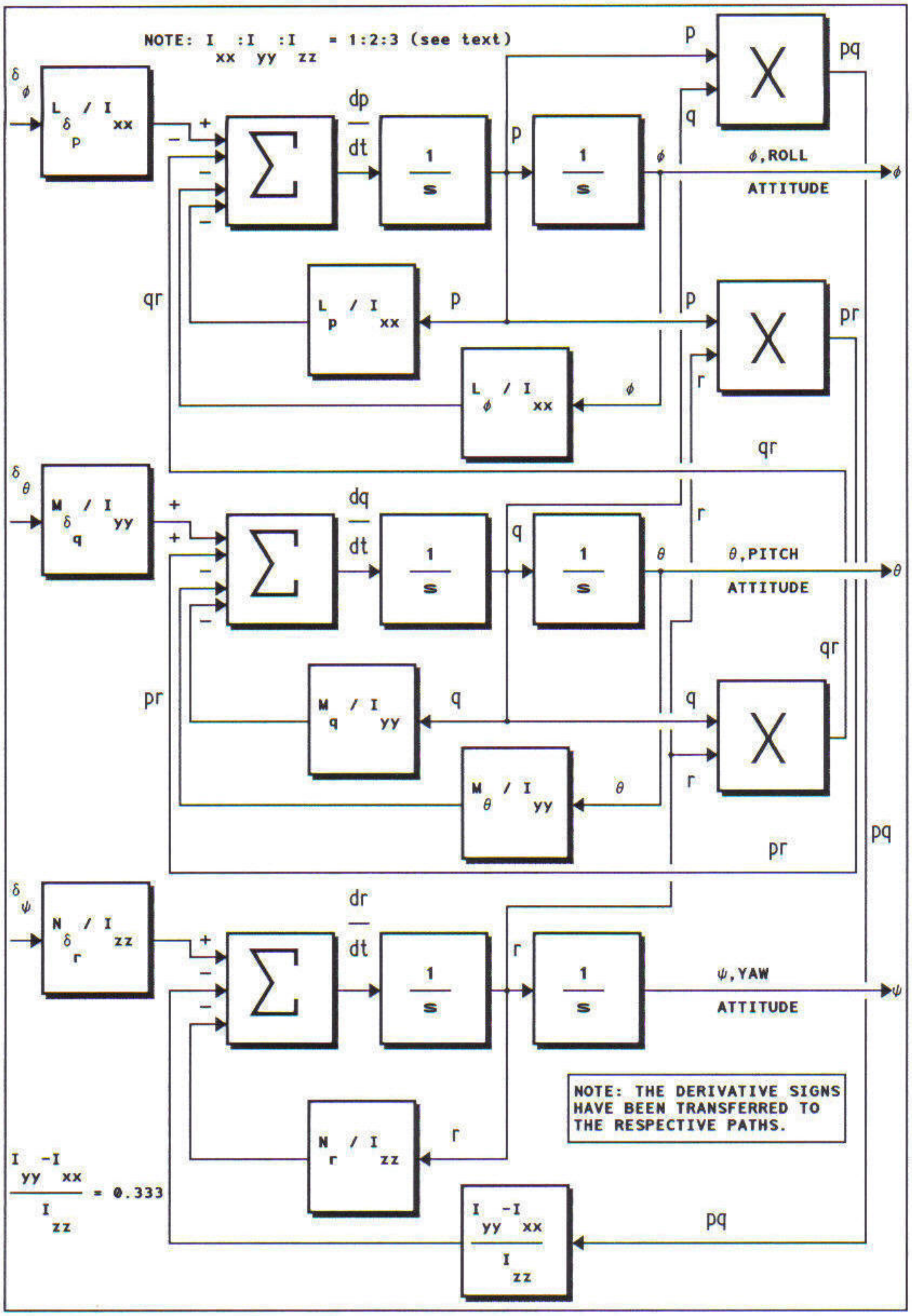

Figure 4 The dynamic structure of the simulated vehicle. The contributions of each derivative's sign and magnitude are clearly shown.

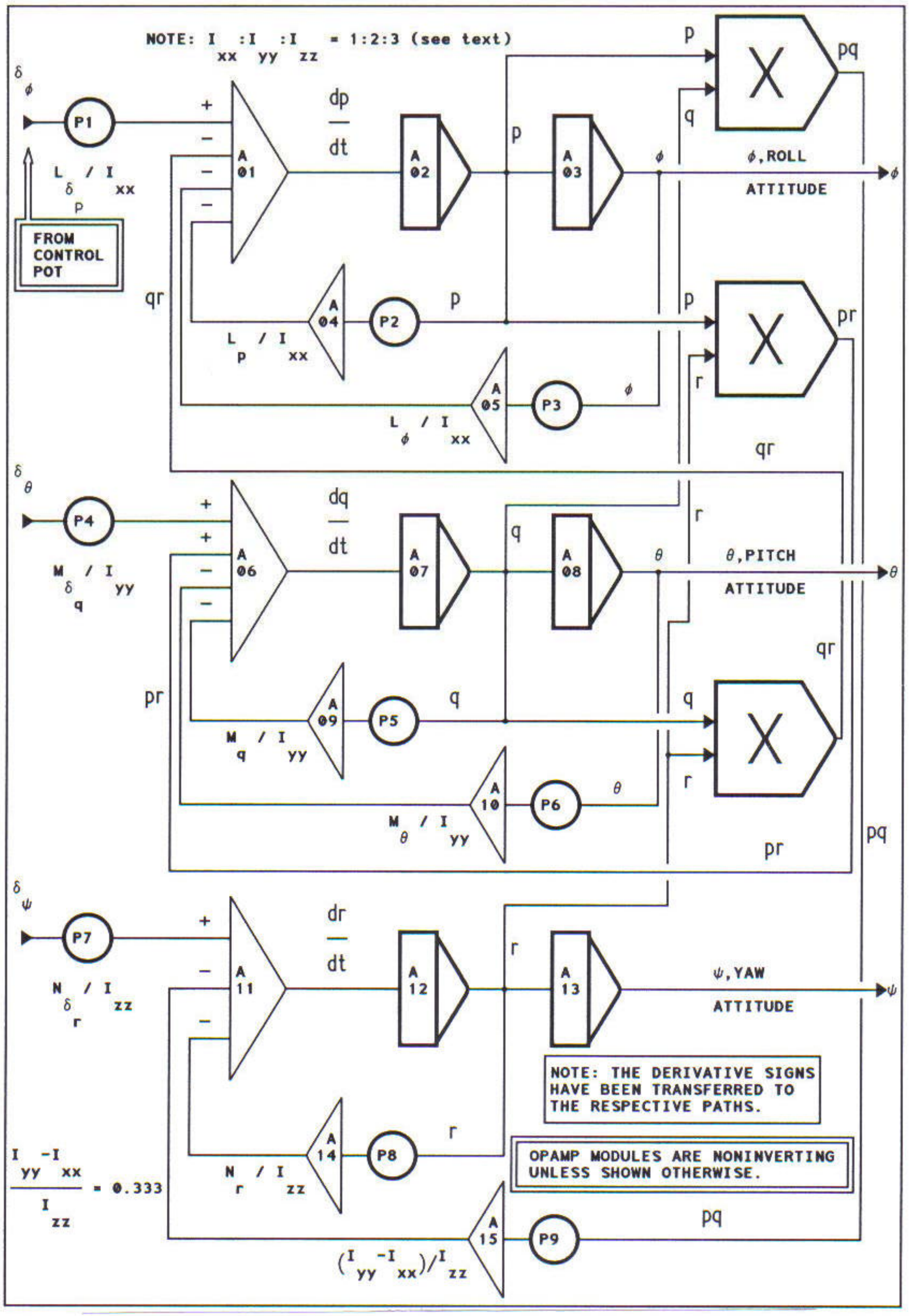

Figure 5 The analog program for the simulated vehicle.