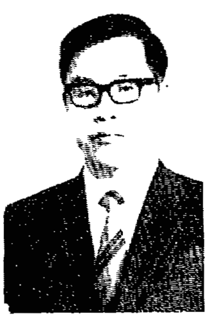
Masami Masubuchi was born in Tokyo on February 1, 1923. He received the B.Engr. degree from the Faculty of Engineering at the University of Tokyo in 1947. After several years' work as a research student, he joined the Faculty of Engineering, Yokohama National University, Kanagawa Prefecture, as an Associate Professor. He received the D.Engr. degree from the University of Tokyo. From 1961, he served as a Professor at the Yokihama National University. Dr. Masubuchi joined the Faculty of Engineering, Osaka University, Osaka, as a Professor in 1969. He has been working on industrial process dynamics analysis and control, and on adaptive control.



Hidenori Kimura was born in Tokyo on November 3, 1941. He received the B.Engr., M.Engr., and D.Engr. degrees from the Faculty of Engineering, University of Tokyo, in 1965, 1967, and 1970, respectively. Dr. Kimura served as an Assistant from 1970, and presently is an Associate Professor in the Faculty of Science and Engineering at the Osaka University in Osaka. He has been working on linear dynamical system theory, design of control systems, and the application of theory to actual processes. Dr. Kimura received an award for his paper in the *Automatica* at the ninth IFAC World Congress.

Yutaka Yoshitani was born in Tokyo on August 30, 1928. He received the B.Engr. degree from the Faculty of Engineering, University of Tokyo, in 1952. In 1952, he joined Fuji Iron and Steel Co. Ltd. (later Nippon Steel Corporation). In 1960, he received the M.Engr. degree from MIT, U.S.A., and the D.Engr. degree from the University of Tokyo in 1981. He joined the Technological University of Nagaoka, Niigata Prefecture as a Professor in 1980. Dr. Yoshitani has been working on instrumentation and control of iron-and steel-making processes. He is also interested in the developing process of technology and technology transfer.

Nicolas Minorsky and the Automatic Steering of Ships

S. Bennett

Introduction

The so-called "three-term" or "proportional + integral + derivative" (PID) control algorithm has been and continues to be very widely used. Its use stems largely from the development of the three-term controllers by the instrument and process control companies. It is claimed that the first three-term controller was introduced by the Taylor Instrument Company in 1936 when *preact*, that is, derivative action, was added to their *double response* controller; initially, the amount of preact was fixed in the factory, but in 1939, a controller with a continuously variable derivative action was introduced [1]. It is interesting to note that it was during this period (1939–40) that George A. Philbrick was developing his electronic analog simulator, which included a three-term controller [2].

The use of derivative and integral action was, in the 1930s, not new: many controllers using it had been designed and used throughout the nineteenth century; it had been recognized early in the work on governors that offset could be removed by the introduction of integral action [3]. What was new was the introduction of general purpose controllers with continuously variable control action. A consequence of the gradual introduction of such controllers into the process industries was a growing interest in the dynamics of various typical processes and attempts to analyze the behavior of controllers [4]. The writers of many of these papers were, however, unaware that Nicolas Minorsky, in 1922, in his paper on the "Directional stability of automatically steered bodies," had analyzed and discussed the properties of the three-term controller [5]: this paper stands alongside those of Maxwell, Routh, and Hurwitz as one of the early formal discussions of control theory.

The paper arose out of work on the installation and preparation for the testing of the automatic steering gear on the battleship *New Mexico*, the trials of which took place in 1923. There had been some interest in fully automatic steering systems almost from the first introduction of servo-controlled steering engines in 1864, but little advance was made until the major naval powers began to review their fire control techniques at the beginning of this century [6]. This review was made necessary by the increasing range of naval guns. The outcome of the review was an increased interest in (i) the development of the gyrocompass — in iron ships, and with the increasing use of electricity in ships, great difficulty was experienced in using the magnetic compass — and (ii) in the stabilization of either the ship or the gun platforms and gun directors. Consideration was given to the possible improvement in accuracy through the reduction or elimination of yaw: "...my first approach to the problem of automatic steering in order to eliminate yaw was therefore made more in connection with gunnery than with navigation" recalled Sir James Henderson in 1934 [7], who was against automatic steering, and this attitude did not change until the successful introduction of the commercial autopilot [8]. So although the tests carried out by Minorsky on the *New Mexico* were successful, the automatic steering was removed and further work discontinued.

Automatic Steering of Ships

Nicolas Minorsky was born on September 24, 1885, in Korcheva, Russia, and died at the age of 85 on July 31, 1970, in Italy. He was educated in the Naval School in St. Petersburg (later Petrograd and now Leningrad) and in 1908 went to study in France in the Electrical Engineering Department of the University of Nancy. He then worked

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at the Imperial Technical School in Petrograd and left in 1914 with a doctorate in applied sciences. From 1914 to 1917, he served in the Russian Navy and was for one year Adjunct Naval Attache at the Russian Embassy in Paris. In June 1918, he immigrated to the United States and remained there until his retirement in 1950 when he decided to go to Southern France, in the foothills of the Pyrenees [9].

During his first four years in the USA, he worked as an assistant to C. P. Steinmetz at the General Electric Company, Schenectady, New York. It has not been established what type of work he did during this period, but it would appear from the evidence of the papers published in 1922 and in 1930 that he worked on automatic steering problems, although in these papers there is no reference to any involvement of the General Electric Company in his work. This work would have been consistent with his interests and experience, since, in 1916, while serving with the Russian Navy, he had made measurements on the sensitivity of the eye in detecting angular velocities. The purpose of the tests was to compare the ability of a person to detect small angular rotations with that of the gyroscopic angular velocity indicator—the gyrometer—which he had invented [10].

Almost from the first introduction of the servo-controlled steering systems in 1864, thought was given to the provision of fully automatic steering: the difficulty was in sensing the position of the compass needle without disturbing the accuracy of it as an indicator. Systems of more limited application were designed, which were to be used either for remote steering or, as in torpedoes, to maintain a constant preset course; for the latter application, gyroscopes were used [11]. The provision of fully automatic steering began to appear feasible with the work, first of Anschutz-Kaempfe and then of Elmer Sperry, on the development of the gyrocompass.

For his expedition to take a submarine to the North Pole, Anschutz-Kaempfe proposed using a compass based on the use of the free gyroscope. He subsequently formed a company to manufacture gyrocompasses, and interest in his work led to developments elsewhere, the most successful being those of the Sperry Company. Elmer Sperry obtained the basic patent for his gyrocompass in 1911, and his first patent for the automatic steering system, the gyropilot, was filed in 1914. Development of the gyropilot was interrupted by the war, and work did not recommence until 1921. Probably the most important aspect of this work was Sperry's development of the *follow-up* mechanism (a position servomechanism), which made available a suitable signal for input to the steering engine [12].

Qualitatively and intuitively, the requirements for good steering were known: "An efficient helmsman keeps the ship accurately on her course by exerting a properly timed *meeting* and *easing* action on the rudder" wrote Minorsky [13]. Sperry [14] expressed the requirement in very similar terms, and Henderson wrote "... the second requirement is *check* helm to stop the swing as the craft approaches a prescribed course..." [15]; he also went on to indicate the need for *weather* or *lee* helm to compensate for the tendency of steady disturbance forces deflecting the ship from the desired course. The questions and problems were to analyze such behavior and to devise means of incorporating *check* and *weather* helm into the steering control. In both these activities, Minorsky was successful. However, he lacked the commercial skills and the backing of an established organization: the commercially successful and widely used system was the Sperry system, described by Dr. A. L. Rawlings, a director of the Sperry Company as "... a very simple machine, and it applies a deviation helm and also a check helm. The method of applying the check helm is frankly a dodge. It is an unscientific dodge. It defies mathematical computation—at least it has defied mine" [16].

Minorsky's attack on the analytical problem was first to argue that good steering was not

> ...so much a question of intuition as of suitable timing based on actual observation.... If, therefore, accurate steering is nothing more than a special kind of timing of the rudder complicated by the inertia of the body to be steered, we may expect to be able to establish analytically what kind of timing must be adopted in order to reach the best possible conditions for directional stability of the body to be steered on its course [17].

His next step was one that was to be characteristic of his approach to problems for the rest of his life: an awareness of nonlinearities in systems, for he immediately simplifies the problem by limiting it to a consideration of small deviations "... for [in] the case of unlimited angular motion... there is no analytical expression applicable to the various torques acting on a ship in general" [18].

Consideration of the dynamics of a ship, including the characteristics of rudders, leads him to an equation of motion, as follows:

$$A\ddot{\alpha} + B\dot{\alpha} + k\rho = D \qquad (1)$$

where α is the angle of deviation of the ship from the desired course and ρ is the rudder angle, A is the effective moment of inertia of the ship about a vertical axis passing through the center of gravity, B is the frictional resistance of the ship to turning, D is the disturbing torque, and k is a constant, depending on the characteristics of the rudder. Thus, providing that the rudder angle ρ is given as a function of the deviation and its derivatives, the problem is completely determined.

Minorsky considered individual cases for various types of regulation, and these are summarized in Table 1. The third class, that of controlling the acceleration of the rudder, was not considered in detail since it is not of practical interest.

Case 1, which uses just the angular deviation to control the angle of the rudder, represents the system that had been tried by several people [19] and leads to a second-order system. Minorsky showed that the damping of the system was dependent on the parameter

$$u = \frac{B}{2A} \qquad (2)$$

and he noted that for ships of increasing size, the term B, representing the frictional resistance to turning, increases at a less rapid rate than the inertia of the ship. He was thus able to explain why *deviation* control, which had been used reasonably successfully on small vessels, did not work on large ships. For cases 2 and 3, he showed that there was no directional stability [20].

Consideration of case 4 led him to conclude

	Class of Control
First	$\rho = m\alpha + n\dot{\alpha} + p\ddot{\alpha}$
Second	$\dot{\rho} = m_1\alpha + n_1\dot{\alpha} + p_1\ddot{\alpha}$
Third	$\ddot{\rho} = m_2\alpha + n_2\dot{\alpha} + p_2\ddot{\alpha}$

Cases.

Case	Class	Parameter	Control Action
1	1	$n = 0, p = 0$	proportional
2	1	$m = 0, p = 0$	velocity
3	1	$m = 0, n = 0$	acceleration
4	1	$m \neq = 0, n \neq 0, p \neq 0$	general case
5	2	$m_1 \neq = 0, n_1 \neq 0, p_2 \neq 0$	general case

Table 1. Cases studied by Minorsky.

that the method "... is efficient from the standpoint of damping out the effect of a disappeared disturbance, but will not eliminate the effect of a steadily acting disturbing torque, such, for instance, as a steady wind." And he noted that in such circumstances, there would be a steady-state error

$$\alpha_1 = \frac{D}{C} \qquad (3)$$

where $C = km$, and that "This first class of steering devices, acting to regulate the angle of the rudder, is unpractical for this reason" [21]. However, he notes that the second class of device in which not "... the *angle of the rudder*, but the rate at which this angle is varied" does not have this disadvantage and, yet, still maintains all the advantages of the first class.

In the second class, the controller has the form

$$\dot{\rho} = m\alpha + n\dot{\alpha} + p\ddot{\alpha} \qquad (4)$$

and substituting for ρ in Eq. (1) gives

$$A\ddot{\alpha} + B\dot{\alpha} + k\int(m\alpha + n\dot{\alpha} + p\ddot{\alpha})\,dt = D \qquad (5)$$

which by differentiating and rearranging gives

$$A\dddot{\alpha} + (B + kp)\ddot{\alpha} + kn\dot{\alpha} + km\alpha = \dot{D} \qquad (6)$$

Minorsky comments that for a steadily acting disturbance $\dot{D} = 0$: "... from which follows the remarkable result that such a disturbance has no influence upon the performance of the device, depending solely upon the inertia A of the ship, the resistance B and the constants, m, n, p, representing the intensities of the corresponding components of the control" [22].

Since the control variable, which affects the course of the ship, is still the angle of the rudder, Minorsky, in his second class of steering device, has in effect changed the characteristics of the controller such that

$$\rho = m\int\alpha\,dt + n\alpha + p\dot{\alpha} \qquad (7)$$

Thus, his first class is a proportional + derivative + second derivative controller, and his second class is a proportional + integral + derivative controller.

Minorsky then goes on to show, using the Hurwitz criteria, that for stability, the following conditions must be satisfied:

$$B + Kp > 0$$
$$(b + Kp)Kn - AKm > 0 \qquad (8)$$
$$Km > 0$$

In a final section of the paper, he considers how control of the second class would behave in the presence of time lags in the transmission system. He considers a controller of the form

$$\rho = \int[m\alpha(t - T_1)]\,dt + n\alpha(t - T_2) + p\dot{\alpha}(t - T_3) \qquad (9)$$

and uses an approximation based on Taylor's expansion, on the assumption that the delays T_1, T_2, and T_3 are small with respect to the period of yawing of the ship, to obtain the following conditions for stability:

$$B + kp - knT_2 > 0$$
$$(B + kp - knT_2)k(n - mT_1) - (A - kpT_3)km > 0$$
$$km > 0 \qquad (10)$$

In his conclusions, he deals with the question of the *anticipation* of angular motion—a current topic was anticipatory control, and we have already noted that when derivative action was introduced into process control, it was called *preact*—Minorsky's comment is that

> ... it is apparent that all possible methods of rudder control *do not actually anticipate* the disturbing angular motion, but merely utilize this motion at its beginning when its value is small for the purpose of impressing a properly timed reaction against it. It is therefore obvious that the disturbing angular motion must necessarily occur *before* any controlling means can be operative (Minorsky's emphasis [23]).

Tests on the *New Mexico*

The tests on the *New Mexico* were carried out by Minorsky for the Bureau of Construction of the US Navy in 1923, although they were not reported until 1930 [24]. The *New Mexico* was chosen for these tests because it was fitted with the Waterbury electrohydraulic steering gear, which, unlike most other types then in use, permitted continuous control action. The measuring instruments used were a Sperry gyrocompass and the so-called *gyrometer*, a device used to measure angular velocity. In spite of his comments on the unsuitability of the first class of control—control of rudder angle—Minorsky used the method for these trials: initially using proportional + derivative control and later introducing an acceleration component into the controller. (In an article in *The Engineer* in 1937, Minorsky claims that control of rudder velocity was used, but in the original article, he clearly states that the first class—control of rudder angle—was used, and examination of the circuits given in both papers confirms this [25]).

The system, including the acceleration control, is shown in block diagram form in Fig. 1. The mechanism used to introduce an acceleration component was very simple—a loosely coupled contact on the gyrometer follow-up shaft—the effect of which is to give a relay action with some hysteresis. The method of combining the signals from the gyrometer, gyrocompass, acceleration and rudder position is shown in Fig. 2. The gyrocompass and gyrometer were both fitted with follow-up motors, such that the angle turned through by the shafts of the motors represented the angular position of the ship and the angular velocity of yaw, respectively. The signals from these were combined using a differential gear, the ratio being fixed at 1:2 (gyrocompass:gyrometer). The output from the differential was used to set the position of the wiper of potentiometer 1. The wiper settings on potentiometers 3 and 3′ were set by the position of the rudder. The voltage supplied from the potentiometer combination was used to provide the field current for a motor-generator set (12, 13 in Fig. 2). In order to provide acceleration control, the lever 6, loosely coupled to the gyrometer

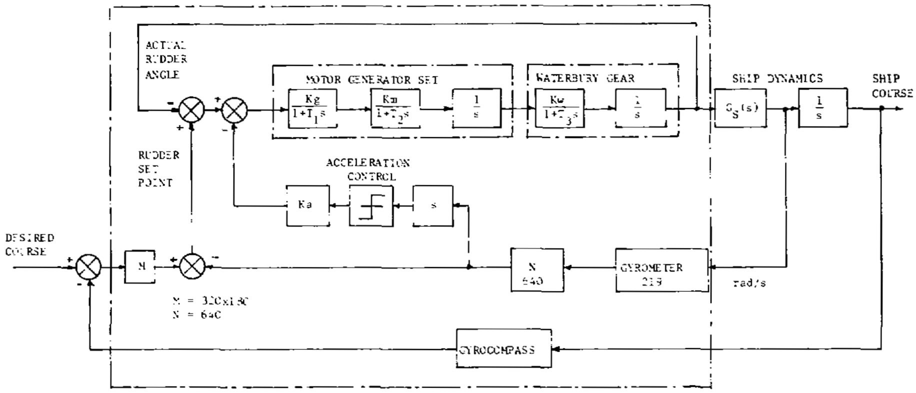

Fig. 1. Block diagram of Minorsky's automatic steering system.

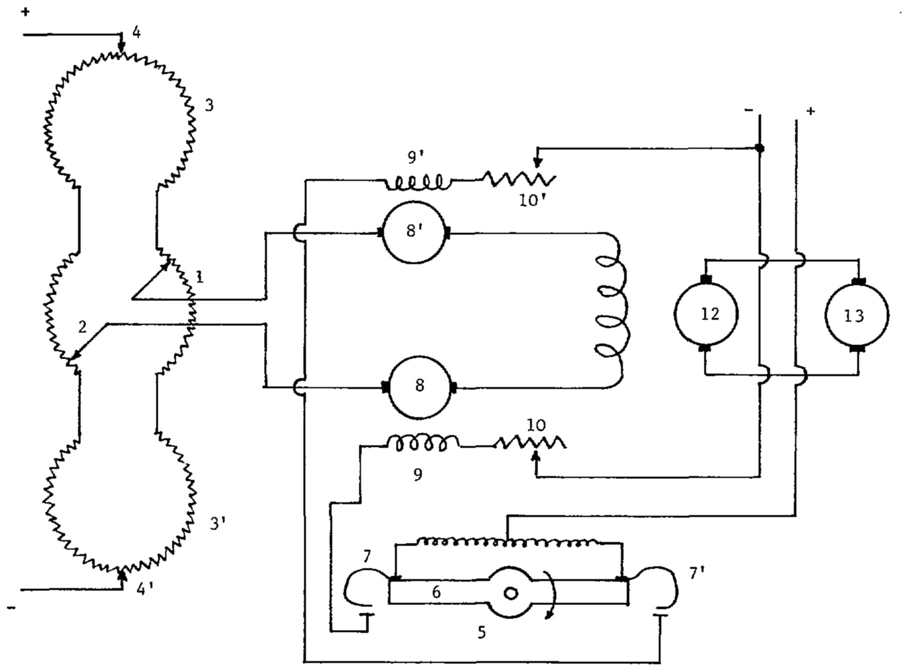

Fig. 2. Controller (Redrawn from Minorsky 1930, *J. Amer. Soc. Naval Eng.*, v. 42).

follow-up system, connected the field supply to one of two booster generators (8 and 8′), which were inserted in series with the field of the generator of the motor-generator set. The amount of boost given was controlled by the setting of the potentiometers 10 and 10′ and, in this way, the amount of acceleration control introduced could be adjusted.

The trials were intended to determine the controller parameters, and it was fairly quickly established that the signal that could be obtained from the gyrometer—the derivative action—was insufficient to give good control: the ship settled down to a motion of ±2 degrees in yaw. This behavior is shown in Fig. 3a, which is based on a simulation of the system. It is in part conjecture, since full details of the system were not given in the paper. From these initial trials, which lasted only a few minutes—the *New Mexico* was at that time on fleet maneuvers—he concluded that two methods could be used to improve performance: (i) to increase the proportion of the gyrometer control or (ii) to introduce acceleration control. He decided on the latter because it was easier to install. A simple system was quickly rigged up while at sea, and this showed promising results; a more permanent arrangement was installed during September 1923. The effect of introducing acceleration control was dramatic; the rudder indicator on the bridge showed no movement—the minimum movement it could show was 5 degrees—and examination of the actual rudder movement showed that it was very small, not exceeding 2 or 3 degrees. The effect can be seen in Fig. 3b, obtained by introducing an equivalent to the acceleration term.

Despite the success of these tests, the gear was removed from the *New Mexico,* and no further work on automatic steering was done until the 1930s, the main reason being, as Captain H. S. Howard of the US Navy explained, that "... the operating personnel at sea were very definitely and strenuously opposed to automatic steering, and they wished us to have nothing further to do with it after these tests were completed" [26]. Between 1923 and 1930, the Sperry Company developed extensively their version of the automatic pilot for commercial use [27], and Minorsky sold his patents to the Bendix Corporation in 1930 [28].

The Sperry system was not described in detail until 1937 when Minorsky analyzed it in his articles in *The Engineer* [29]. He showed that the so-called *dodge* was in fact a method of introducing acceleration control, and Sperry's system used proportional + acceleration control of the rudder angle. As Fig. 3c shows, it was an effective combination, and automatic steering systems manufactured by the Sperry Company came to be widely used.

Minorsky's Later Work and His Influence on Control Developments

From 1923 to 1934, Minorsky worked at the University of Pennsylvania as a professor in the field of electronics and applied physics; he then joined the US Naval Research Laboratory and worked at the David Taylor Model Basin, largely working on the stabilization of ships against rolling. His main concern was with the active tank method of stabilization, and he made both practical and theoretical contributions to the work in this field. During the war, he was special consultant to the director of the David Taylor Model Basin, in which capacity he worked largely on stability problems: it was during this period that he became increasingly interested in nonlinear systems. In 1946, he joined the Division of Engineering Mechanics at the University of Stanford where he continued to work on ship stabilization problems and on

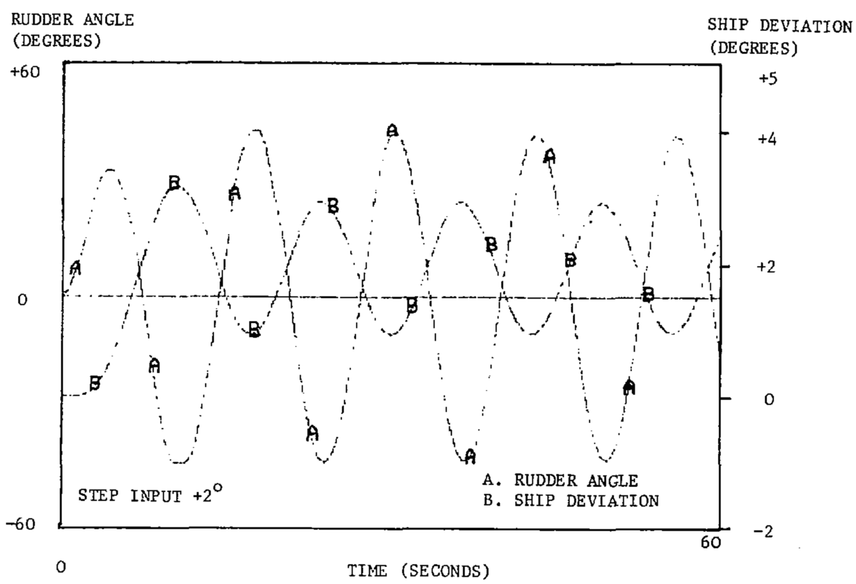

Fig. 3a. Proportional + Derivative Controller.

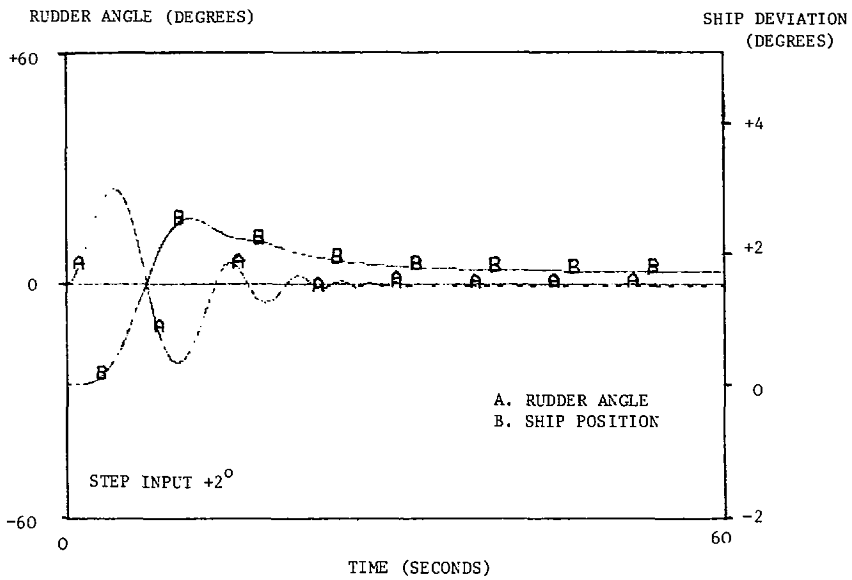

Fig. 3b. Proportional + Derivative + Second Derivative Controller.

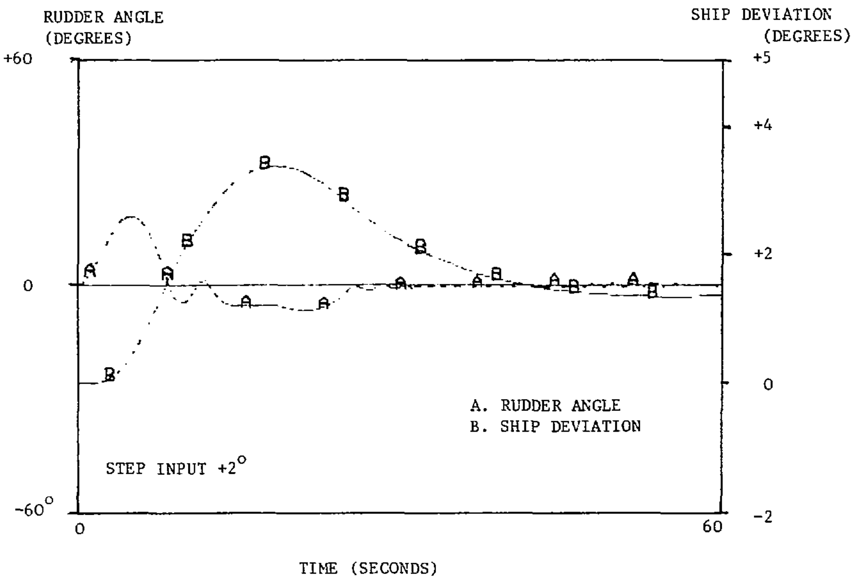

Fig. 3c. Proportional + Second Derivative Controller (Sperry System).

his growing interest in the area of nonlinear mechanics. This was an area in which he continued to work after his retirement from Stanford at the age of 65 in 1950; his last paper was published in 1968, just two years before his death in 1970 [30].

Minorsky's early work on automatic steering influenced Harold Hazen and this can be seen in Hazen's papers on servomechanisms, published in 1934. These papers were to form the basic reading of many of the early control engineers [31]. Other than this, the 1922 paper was not very widely known, and outside the field of naval engineering, Minorsky and his work remained largely unknown until a series of articles by him were published in *The Engineer* in 1937. To the few who discovered the papers, however, the work was significant in that it presented a clear theoretical understanding of the problems. Furthermore, the operation of the practical devices proposed could be clearly understood and related to theory, thus providing a good basis for future developments and a transfer of the principles to analogous problems. In contrast, the gyropilot work of the Sperry Company, although commercially successful, was based upon the intuitive understanding of Elmer Sperry, and the principles were not clearly understood until Minorsky analyzed the system in 1937.

In 1941, Minorsky published a long paper in the *Journal of the Franklin Institute* in which he dealt with a variety of linear and nonlinear control problems and outlined a method of analysis based on operator techniques [32]; in this, he drew from the work of Norbert Wiener on the operational calculus [33]. This paper, in fact, received little attention, for it lacked the simplicity and immediate ease of understanding of other contemporary papers, for example, the paper by H. Harris published in 1941 and the later papers to come out of the wartime work of the Radiation Laboratory at MIT [34]. It did, however, mark the change in the direction of Minorsky's work toward nonlinear problems, and his major contribution in this area was to draw attention to the work of the Russian mathematicians, in particular, that of Liapunov and the then new work of Bogoliubov and Krylov [35].

Following his retirement from teaching, he continued to work for his adopted country through contracts for the Office of Naval Research and continued to follow closely developments by Russian authors, work which he reported on in his last book, published in 1969; however, through translation programs, much of the Russian work was widely known, and the exchange of ideas was taking place through the IFAC meetings. Minorsky was not fully aware of the developments that had taken place in the USA. Because of this, his later work was not as important as, for example, the book *Introduction to Nonlinear Mechanics*, published in 1947, which became a work of reference for workers in the field of nonlinear control [36].

Let us leave the last word to Flugge-Lotz who, writing in 1971, remembered "...the tall slender man presenting the 'grand seigneur' type when he was walking with his characteristically bent soft-felt hat over the Stanford campus, perfectly absorbed in his scientific ideas" [37].

Acknowledgments

I wish to thank J. G. Ziegler for providing me with a copy of his reminiscence and Dr. David Allinson for providing a list of references to Minorsky's work at the Naval Research Laboratory. I am also grateful to Professor H. Nicholson for his constant support and encouragement. I also acknowledge the support of the Research Fund of the University of Sheffield for part of this work.

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[14] Hughes, op. cit., p. 280.
[15] Henderson, op. cit. p. 22.
[16] Ibid., p. 28.
[17] Minorsky, 1922, op. cit., p. 283.
[18] Ibid.
[19] Andrew Betts Brown experimented with automatic steering using position control in the latter part of the nineteenth century; see Henderson, op. cit. discussion, pp. 30–31.
[20] In the nineteenth century, many people had attempted to design governors that dispensed with proportional action — the so-called isochronous governors — only to find that there was no control over the speed at which the governor exerted regulation; see Bennett, op. cit., Chap. 3.
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[36] N Minorsky, *Introduction to Nonlinear Mechanics,* Ann Arbor: J. W. Edwards, 1947.
[37] Flugge-Lotz, op. cit., p. 290.

Stuart Bennett is a Lecturer in Control Engineering at the University of Sheffield. Following an apprenticeship with the British Aircraft Corporation, he spent four years on research on lubrication of components for spacecraft. He joined the Control Engineering Department of the University of Sheffield in 1968, where his main interests have been computer control and the history of control engineering. He is the author of a book on the history of control engineering and, during 1982, spent six months as a visitor at the Museum of American History, Smithsonian Institution in Washington, DC.

Conference Calendar

Date	Conference	Location	Contact	Deadline
Nov. 28-30, 1984	Symposium on New Technologies in Nuclear Power Plant Instrumentation & Control	Washington, DC	J. Louis Tylee, I&C Symposium, EG&G Idaho, Inc., P.O. Box 1625, WCB W-2 Idaho Falls, ID 83415	Past
Dec. 5-7, 1984	International Conf. on Road Traffic Data Collection	Savoy Place, London	Manager Conf. Services, Inst. of Elect. Engineers Savoy Place, London WC2R OBL, UK	Past
Dec. 10-12, 1984	IEEE International Conference on Computers, Systems, and Signal Processing	Bangalore, India	I. G. Sarma, School of Automation, Indian Institute Science, Bangalore 560 012 India	Past

Continued on p. 23