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Early Control Development in Sweden

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This article gives a glimpse of the early development of automatic control in Sweden covering the period up to the mid 1960s. Much of the early developments took place in industry and the defense establishments. Process control, particularly in the pulp and paper industry, power systems, and military projects were strong drivers for the technology. The article ends with the emergence of control in academia and interaction with International Federation of Automatic Control (IFAC).

Keywords: Automatic control; history; process control; power systems; missiles; aircrafts; education

1. Introduction

Sweden is a small country where industrialization came quite late. In spite of the late start, Sweden has development and manufacturing of cars, communications systems, mobile phones and systems, nuclear reactors, and advanced military aircrafts and satellites. It is interesting to reflect on how this could have happened. One reason is that Sweden has excellent higher education, another is that there has been a strong collaboration between companies and state agencies. Sweden was lucky not to be in the war, but as it was neutral, it was necessary to have a national defense industry to guarantee supply of equipment.

Sweden had traditional universities and two engineering schools, the Royal Institute of Technology (Kungliga Tekniska Högskolan, KTH), in Stockholm and Chalmers Technical University (CTH), in Göteborg, which were founded in 1826 and 1829, respectively. In the 1920s, the engineering schools focused more on research. KTH was given the right to award PhDs in engineering in 1927. A special program Engineering Physics (Teknisk Fysik) with a strong emphasis on basic science was introduced at KTH in 1932. The goal was to educate engineers for the research laboratories that emerged at that time. The program admitted only a small number of students. In my class in 1953 we were 13 students. It was a very good program. Full professors gave the lectures and we probably learned as much from the informal discussions as from the lectures. Those of us who were theoretically inclined also followed lectures on probability by Prof. Ulf Grenander at Stockholm University and on mathematics by Lars Hörmander. Hörmander did his military service at the National Defense Research Establishment (Försvarets Forskningsanstalt, FOA), but was stationed at KTH where he lectured on functional analysis and measure theory. We also formed a study group *Friends of Algebra* that met once a week for more than a year. University education in control started in the 1950s at KTH and CTH. The first professorship in control was created at KTH in 1960, followed by CTH in 1962, and Lund Institute of Technology (Lunds Tekniska Högskola, LTH) in 1965. LTH later became the technical faculty of Lund University.

Activities in automatic control followed the industrial development. The pulp and paper industry and the power industry were strong drivers for the early development which was dominated by entrepreneurs. They created companies based on inventions of devices for sensing, actuation, and control. IBM started a laboratory for computer-based process control in

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Stockholm in 1960, but IBM's activity in process control only lasted for a limited period. The development of the power industry had a strong focus on research and development and there were strong interactions between the Swedish State Power Board (Vattenfall) and Asea.

The military development had a major impact on technology. Sweden had a weak defense establishment at the outbreak of World War II. Because of its neutral position it was necessary for Sweden to have independent weapons production. A major difficulty was that borders were closed, and that much information was classified. Therefore, it was necessary to develop the knowledge domestically. The Royal Swedish Air Force Board (Kungliga Flygförvaltningen, KFF) and similar agencies for the Army and the Navy worked closely with industries like Saab, AGA, Bofors, LM Ericsson, Philips, and Volvo. FOA, which was established in 1945, had significant research efforts in control. Because of decisive actions, and a strong agile engineering industry, it was possible to build a diversified defense industry for production of airplanes, tanks, ships, and ammunition. For a while Sweden even planned to build nuclear weapons. Uranium was mined and nuclear reactors with heavy water and natural uranium were built. There were several large military projects in the 1950s and 1960s that had a major impact on development in control. The largest project was the airplane 37 Viggen [43] which was based on extensive studies from 1952–1962 followed by design and manufacturing. The Viggen project was a major effort. At its peak, more than 2000 persons were engaged in development at Saab and several hundred at LM Ericsson with radar development. There were many other projects where control was important. Let me just mention the company Bofors, founded in 1646 and acquired by Alfred Nobel in 1893. The Bofors 40 mm anti-aircraft guns are well known all over the world. It is widely recognized that the hydraulic control systems and the electronic fire control are key components in the system.

There were strong synergies between control and computing in the early development. Analog computing was used for simulation and implementation of early control systems. Digital computing had an even greater impact. In Sweden, there were developments of analog computing in the Aeronautics Department at KTH and at the Department of Electrical Engineering at CTH. FOA, Saab, Asea, Bofors, and other industries also developed major centers for analog computing. Four researchers were sent to the USA to study computer development in 1947 and the Swedish Board for Computing Machinery (Matematikmaskinnämnden, MNM) was created in 1948 to provide computational capabilities for government agencies. An attempt was made to buy an electronic computer, but this was not possible because of export restrictions, and MNM decided to build its own computer. A digital computer called BARK based on relay technology was built in 1950. The electronic machine BESK, which was a copy of the von Neumann machine, became operational in late 1953. It was used for a wide range of applications and had a profound impact on the development as will be described in the following.

2. Process Control

As in many other countries, the early development of control in Sweden was driven by entrepreneurs, who invented devices and built industries based on them. The pulp and paper industry, which is one of Sweden's most important export industries, was a fertile ground for development of control. There was a central research laboratory STFI supported jointly by industry and government under TFR. The major activity at the institute focused on paper chemistry. There was some activity in control, particularly development of new instruments.

2.1. Early Entrepreneurs

Nils Gustaf Dalén graduated in chemical engineering from Chalmers in 1896. After graduation he spent a year with Prof. Stodola at ETH in Zürich. After working for Svenska Karbid- och Acetylen AB, he joined the Gas Accumulator Company in 1906 where he became chief technical officer. The company was later reorganized as Svenska Aktiebolaget Gasaccumulator (AGA Swedish Gas Accumulator Ltd.) with Dalén as the managing director. Dalén was awarded the 1912 Nobel Prize in Physics with the citation: "*For his inventions of self-operating regulators which in combination with gas accumulators can be used to light lighthouses and light buoys*." The sun valve, which has four metal rods enclosed in a glass tube, was a key component. One rod is black, the others are polished. Daylight is absorbed by the black rod which expands and closes the gas valve. When daylight decreases, the black rod contracts and opens the valve. The sun valve combined with intermittent light saves more than 90 per cent of the gas. It enabled lighthouses to function unattended for periods of up to one year. Dalén also invented a safe way to store acetylene by compressing it in a porous mass, called aga, which became the name of the company. The company AGA expanded into gas welding, manufacturing of radios and TVs, batteries, gyroscopes, and optics for distance measurements and thermal measurements. AGA also played a major role in the development of military equipment because of its expertise in precision mechanics, optics, and electronics. AGA is now part of the Lindhe Group which is a global gas company.

Stig Billman graduated from KTH in 1929. He wrote a masters thesis on thermal processes and temperature controllers. After graduation he worked for a small company, Birka regulator, which developed automation of oil burners. Billman started his own company Billman-Regulator in 1932 working out of a small apartment in Stockholm. He was a creative entrepreneur, who saw drawbacks with the existing equipment, and started to develop and produce new products. A key component was a valve driven by an electrical motor, where a relay was used as a high-gain amplifier. Linearity was achieved through the use of feedback. The scheme, which is called thermal feedback, admits the long-time constants required in temperature control systems.

Torsten Källe graduated in Chemical Engineering from CTH in 1919. After graduation he worked at the paper company Billerud AB. In 1921, he founded the company Källe-Regulatorer for manufacturing of controller and instrumentation for the pulp and paper industry. A key component was an electro-hydraulic controller which was widely used in the pulp and paper industry. Källe also developed sensors. One of them was a unique sensor for pulp consistency. The sensor was nicknamed the Carrot because of its shape.

There were many other companies. Nordiska Armaturfabriken (NAF), established in 1896, originally developed valves and pressure sensors. During the World War II, they manufactured instrumentation for aircraft, such as gyro horizons. After the war the company had agencies for process control instrumentation and later they manufactured their own controllers. A pneumatic PID controller was one of the successful products. Later in the 1980s, the company commercialized the relay auto-tuner for PID control [11]. After several acquisitions NAF is now integrated with ABB.

2.2. The IBM Nordic Laboratory

The idea to control industrial processes using digital computers emerged in the late 1950s. Texaco installed a RW-300 computer for supervisory control at the Port Arthur refinery in Texas in 1959. There were strong expectations about computer control in the 1960s inspired by the early installation. IBM and other computer companies saw a large market potential. IBM started a research group for control with Rudolf E. Kalman as the leader. After a short time Kalman left and was succeeded by John E. Bertram. Both Bertram and Kalman were PhDs from the group at Columbia University led by John. R. Ragazzini and Lotfi A. Zadeh. IBM also started the Nordic Laboratory in Stockholm in 1960 with responsibility for computer control. Kai Kinberg was a dynamic laboratory leader, and the lab grew quickly to several hundred persons. I started to work at the laboratory in 1961. I also had the benefit to work at IBM's research laboratories in Yorktown Heights and San Jose in 1962 and 1963. Bertram maintained good relations with Kalman who gave several short courses at the San Jose laboratory. We also regularly attended seminars at Berkeley, Stanford, and Lockheed. The contacts I developed during my stay at San Jose were very important for my career and I also became firmly convinced that research in control was an exciting future. Kinberg stimulated interactions with the engineering schools in Scandinavia by arranging seminars and symposia. An extended visit by Richard E. Bellman was also sponsored in collaboration with the Mathematics Department at KTH [15]. Bellman strongly encouraged me to write a book on stochastic control [8].

The Billerud Company in Sweden had a far-sighted research director Tryggve Bergek, who had the vision that computer control could benefit the pulp and paper industry. Bergek had explored several avenues to implement his vision. He had contacted Saab for a possible collaboration based on Saabs D21 computer [66], which had been used in a project for production control for Skandinaviska Elverk, but Saab declined. Bergek contacted Kinberg and a joint project on control of paper manufacturing was started in April 1963 [6]. One objective of the study was to develop technologies for computer control, another objective was to explore computer architectures suitable for computer control. A feasibility study that ran for five months was first performed. A result was to implement an advanced process control system with the tasks of production planning, production supervision, on-line process control, quality control, process data collection, and reporting. The idea was to squeeze as many applications as possible into a computer system. A computer system was installed in December 1964. The process controller IBM 1710 was based on an IBM 1620 computer, which had been provided with interupts and a process interface. From today's perspective it seems quite surprising that so much could be done with such a small system. Experiences from the project were fed into the development of the process control computer IBM 1800. Many of the features that we found useful for process control are also useful for general computing as evidenced by the development of the IBM 360 computers. IBM explored the option of becoming a major player in process control by acquiring an instrument company but decided not to do so because of the American anti-trust laws.

Two ideas generated in the IBM-Billerud project were the maximum likelihood method for system identification [10] and the minimum variance control strategy [7]. Experiments with system identification of paper machine dynamics started in 1965. Closed-loop minimum variance control of basis weight and moisture was operational in the spring of 1965 and the complete system was operational a year later. The project was successfully completed, the results were disseminated in a Symposium in 1966 [20–22]. The proceedings were unfortunately not published in book form. All of us who participated learned a lot and many of us returned to academia, Torsten Bohlin, Jorma Rissanen and I became professors of control at KTH, Linköping, and Lund. The problems and experiences we brought with us were inspiration for much of our research in years to come.

3. Power Generation and Distribution

The first electric networks were small local systems with DC transmission. The Vattenfall was created in 1909 to exploit electric energy from the rivers owned by the state. There was a mixed ownership consisting of local distributors and power producers with regional monopolies. The development was stimulated by collaboration between Vattenfall, Asea, and the private power companies. There were significant innovations in development of turbine governors, control principles for power systems, and technology for high voltage direct-current (HVDC) transmission. Both Asea and Vattenfall contributed to the development. A broad perspective on the development is given in [26].

3.1. High Voltage Alternating Current (AC) Transmission

The collaboration between Asea and Vattenfall was very successful and it resulted in a dynamic development of transmission of power generated in rivers in northern Sweden to power consumers in the south. There were significant component and systems problems in power transmission over long lines. The major component problems were related to insulation, transformers, and breakers. Here I will focus on systems problems with connection to control.

Ivar Herlitz was an engineer at Asea, who had worked on high voltage transmission for a few years. He took a leave to study in the USA in 1920–1922. He went to Harvard University, General Electrics research laboratory, Union College in Schenectady, and Stanford University. For a period he also worked for Riverside South Sierras Power Co in Riverside California, which had several long high voltage transmission lines. When Herlitz returned to Sweden he wrote a PhD dissertation [37] on dynamic stability of power transmission systems. The potential instability caused by large perturbations (*transient stability*) was investigated using a simple model for a generator connected to a strong grid. Herlitz made approximations and arrived at the *equal area criterion* for stability to large perturbations. This criterion, which gives good engineering insight, is still in use [45].

In 1946 Vattenfall decided to build a 380 kV transmission line. Major developments were made at laboratories both at Vattenfall and Asea. The new line, which had a length of 952 km, was commissioned in 1952. At that time it was a world record both in voltage and length [26]. Power systems are nice examples of distributed dynamical systems which can exhibit complex behavior. Severe difficulties in terms of undamped oscillations were encountered in the late 1960s when a network connecting the Scandinavian countries was built. It was observed that a small perturbation in one of the tie lines could generate large fluctuations in the whole network, a typical example of a large-systems problem. Vattenfall made extensive investigations based on experiments and large computer simulations [53]. The experiments consisted of disconnecting lines at various points of the network and observing the consequences. The simulations showed that the oscillations could be avoided by using supplementary signals for excitation control of the generators.

3.2. HVDC Transmission

Even if power is predominantly transmitted using AC, there are situations when HVDC transmission has advantages. Typical examples are long submarine cables and asynchronous links between AC systems. There are many challenges in HVDC transmissions. Components are needed to convert from AC to direct current (DC) and vice versa. HVDC systems are highly controllable and can change large amounts of transmitted power very quickly. To obtain a good system it is necessary to have sound control principles that permit a safe operation of the systems. HVDC systems thus have both component and system challenges.

Vattenfall and Asea carried out a joint development project that led to several innovations. The initial key development was made by Uno Lamm, a graduate from KTH, who was hired by Asea in 1927. In 1943 he got a PhD based on his research at Asea. The first breakthrough came in 1954 when a 20 MW 100 kV line between the mainland of Sweden and the island of Gotland was taken into operation. Asea became a world leader in HVDC and later delivered many similar systems all over the world, first with mercury arc valves and later with thyristor valves. The impact of the collaboration between Asea and Vattenfall is described in [26] and [31]. More personal accounts are found in [14] and [33].

The power transmitted on AC lines is determined by the phase-shift between the voltages of the sending and the receiving stations, the inductance of the line, and the voltage levels. For a HVDC system, the transmitted power is instead determined by the resistance of the line and the voltage levels. As the resistance of the line is usually small, the transmitted power can be controlled rapidly, by fast control of the voltage in one of the stations while keeping the voltage at the other station constant.

The first control systems for HVDC transmission were designed based on engineering insight and analysis. As the primary actuators were switches, the control system was a mixture of analog control and discrete logic. Logic was important both for control and for maintaining the safety of the system. The complete system is an example of what we today call a hybrid system. The complexity of the systems made analysis very difficult; elaborate simulators were therefore built to enable simulations of the systems. It was not until the beginning of the 1960s that the full benefits of the fast current control system were taken into account when designing the main power circuits. Expensive extra damping power circuits could be avoided by proper design of the control system. Frequency response methods were useful for understanding the interaction between the AC and DC sides. It was particularly useful because the converters were also used as frequency converters. The resonances created by the inductances and capacitances in the HVDC and AC systems were often critical for the operation of the system. The deep understanding of the systems gave a good competitive advantage and publications were delayed [55].

Even if there were major component innovations, the systems innovations were equally important. The engineer Lamm who was in charge of the early projects called it *Radical Systems Technology* [46]. Many of the novel control principles, developed for the first HVDC systems, could be used later when technology changed and mercury-arc valves were replaced by thyristors, [21,23]. It is an illustration of the fact that good control principles can survive several generations of technology.

3.3. Asea's Central Laboratory – Frequency Response

Asea had a central laboratory led by Aage Garde. There was a strong control group. Erik Persson was one of the key control engineers in the laboratory. Electro-hydraulic controllers were developed for water turbines and electric furnaces [28–30, 35, 36]. Many control studies were also made for HVDC systems [55].

For a long time control systems were investigated by analyzing the roots of the characteristic equation. This was a major effort because computational tools were not available. In the end of the 1940s, Asea learned about frequency response, perhaps from a course given in Stockholm in 1948 by Prof. Campbell from Gordon Browns Servomechanism Laboratoy at Massachusetts Institute of Technology (MIT). In the late 1960s, I invited Garde and Persson to lecture in Lund about the control development at Asea. I remember vividly how they emphasized the dramatic impact of Nyquist's stability criterion and modeling and design based on frequency response. According to Garde and Persson, Nyquist's stability criterion transformed control system design from an ad hoc procedure to a systematic design method [28].

Asea developed an effective methodology for analysis and design of control systems based on frequency response. Models were developed by injecting sinusoidal signals and measuring amplitude and phase relations between inputs and outputs. Correlation techniques were used to obtain accurate measurements of the transfer function [3]. Linearity was assessed by repeating experiments with different amplitudes of the excitation signal. Control systems design was performed using graphical methods based on Nyquist and Bode plots. A frequency response method for design of MISO systems was developed [30]. The Asea engineers were fearless in making experiments on real systems to obtain their dynamics. The paper [30] describes how the frequency responses of a submarine was determined by manual signal excitation and manual signal recording. The paper [3] describes how the dynamics of the Swedish power network were determined by injecting large sinusoidal signals from a power station. These experiments were an inspiration for us when we later applied system identification to real industrial processes. The paper [51] was included in the book [52] which became a standard source for frequency response.

3.4. Nuclear Power

The Swedish policy of developing nuclear weapons led to mining of uranium and a program of building reactors based on natural uranium and heavy water. An experimental reactor was built close to KTH. A separate company AB Atomenergi was created to develop the reactors, one reactor was built and another was projected. In 1958, the social democrats made a study, which concluded that there were many reasons why Sweden should not have nuclear weapons, but that a formal decision to cancel programs could wait [27,41]. The development program of heavy water reactors was stopped when the nuclear weapons program was cancelled. Atomenergi merged with Asea's nuclear program to form the company AseaAtom and boiling water reactors were built. AseaAtom delivered 9 of the 12 Swedish reactors. Asea also developed training simulators and control systems for the reactors.

4. Defense Research

There were several loosely organized activities to engage scientists in military activities before and during World War II. FOA was created in 1945 to centralize military research. It was organized as an applied problem-driven research institute with sections for chemistry, physics, and electronics [24]. FOA had a very good interaction with academia. Many researchers were recruited from academia and researchers from FOA later became professors. FOA has also created groups for fundamental research in areas where no academic research was available in Sweden; some examples are automatic control, optimization, systems, lasers, and image processing. FOA's research in guided weapons, missiles, and torpedoes which started in 1945 had a strong impact on control [39]. Originally there was one group devoted to control theory, critical components, and missile systems. The group was led by Thorvald Persson. Later a separate group, lead by Jonas Agerberg, was created to deal with analog computing and missile systems.

The component development focused on servos, platforms for guided missiles, inertial sensors, and fluidistors. Pneumatic and hydraulic servo valves were developed in collaboration with Prof. J.L. Shearer at MIT [16]. The development was later switched to pulsed servos. Gyros are essential components in guidance systems. FOA developed spherical gyros with air bearings and prototypes of laser gyros. A high precision test bed for measuring gyro performance was also developed. Missile guidance was a major application.

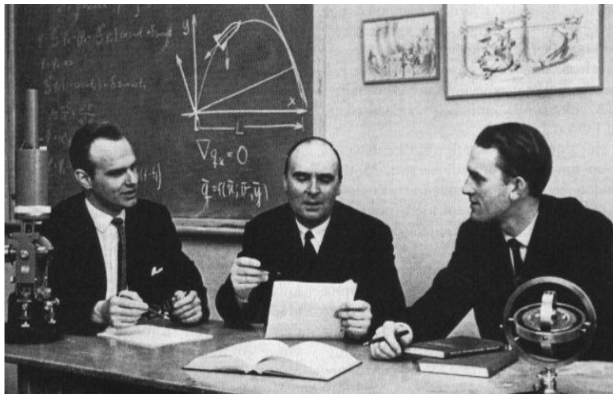

Fig. 1. Discussion of inertial navigation at FOA in the 1960s. From left to right Gunnar Brodin (later Professor at KTH, rektor of KTH, chancellor of the Swedish Universities, governor of the province of Norrbotten and riksmarskalk), Thorvald Persson lab director, and Svante Jahnberg, from [24].

4.1. Missile Guidance

Invasion across the Baltic was one of the major military threats to Sweden. Efficient measures to counter this threat were a major concern. It was one of the reasons why nuclear weapons were considered. Sweden got an early start because a German V1 missile fired from Penemünde landed near the city of Karlskrona in November 1943. The missile was closely investigated and the Navy ordered copies to be built by Saab and STAL. The first systems were tested in 1946 and several hundred missiles were built. More information about missile technology was obtained in 1944 when a German V2 missile crashed in the village Bäckeby.

Original contributions to missile guidance were given by Lars Erik Zachrisson, a graduate in Engineering Physics from KTH, who joined FOA to work on missile guidance. He made analytical studies of pursuit strategies. Zachrisson discovered proportional navigation independently and he proved that the navigation constant must be less than 2 to have a stable pursuit [70–72]. Today it is known that proportional guidance was first proposed by Yuan at the RCA laboratories in 1943. His work was later

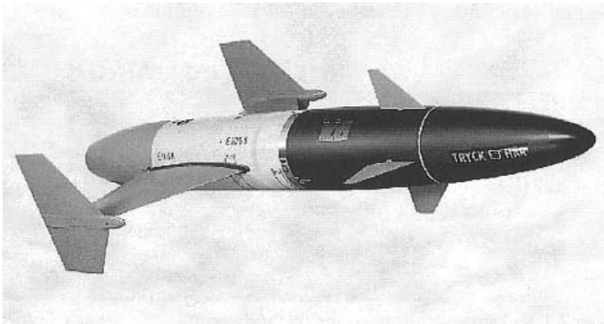

Fig. 2. The missile RB 04, one of the early air-to-sea missiles was developed in collaboration of KFF, FOA, and several Swedish industries [62] page 208.

declassified and published in Journal of Applied Physics from 1948 [69], two years after Zachrisson's patent. The name proportional navigation did not appear until 1956 [1].

Many projects at FOA were directly funded by KFF. There was also a close collaboration between FOA and KFF. Bengt Sjöberg, who graduated in engineering physics from KTH in 1954, was hired by KFF to simulate missile guidance on the BESK computer. Sjöberg was also a teaching assistant in my first control course at KTH, and he got me interested in control. Zachrisson worked closely with Agerberg of FOA's simulation group to investigate different guidance laws. An interesting hardware test was also performed using two trucks on an air field in the early 1950s. One truck represented the target, the other the missile. The target had a searchlight. The other truck, which simulated the missile, had a simple optical target tracker built from photo cells, mirrors, and rate gyros.

FOA's electronics group developed radar target trackers for the missiles [24] which were incorporated in an air-to-sea missile. KFF, FOA, AGA, Saab, and several other industries collaborated in the development [62]. FOA developed guidance laws and the target tracker. The development resulted in the missile 304 (later renamed as RB04) which became operational in 1962, see Fig. 2.

4.2. Analog Computing and Simulation

Computational tools are required to simulate missile systems and other guided weapons. Analog computing was the only solution available up to the 1960s. FOA's group for missile studies became a center for analog computing. FOA started with a Philbrick computer and a home-built machine. Commercial machines were later bought from Electronic Associates in the USA. The studies included evaluation of a wide range of missile systems, design of control systems for guided missiles based on proportional navigation, and analysis of the effect of flares on infrared guidance. Later FOA's missile activities were focused on making KFF a competent buyer by evaluating the missile systems that were bought from different vendors.

FOA's analog computing group under Jonas Agerberg organized education and information exchange in analog computing. The first Swedish course in analog computing was organized by FOA in Stockholm in 1957 with over 100 participants. FOA created the Scandinavian Analog Computer Association (Skandinaviska Analogimaskinsällskapet, SAMS) for users of analog computing. SAMS was very active writing handbooks and organizing two meetings every year. The prime participants were FOA, KTH, and a large number of industries and research institutes in Scandinavia. The meeting originally focused on good analog computing practice but later they centered on applications. As many of the applications were related to control, the SAMS conferences became the first organized meetings of control in Sweden. The organization SAMS still exists but it is now focused on modeling and simulation.

4.3. Systems and Operations Research

In the early 1950s, there was a growing awareness of the military importance of operations research [24, 42]. Zachrisson also worked on several operations research problems. When analysing tank battles he found that they could be formulated as a Markov game for dynamical systems, see [73,74] and many internal FOA reports. Isaacs had published an internal report at RAND already in 1951, but this work was not available to Zachrisson in 1955, and Isaacs' book [38] was not published until 1965 [17]. A planning office, called FOA P, was created in 1958 to deal with operations research. The activity was at a comparatively low level with a small central group for methodology development and analysts and staffs of the Army, Navy, and Air Force. To ensure that there was education at universities, FOA P placed a group for research and education in Optimization and System Theory at KTH in 1963. Zachrisson, who had left FOA to work at Saab's R-System group in Linköping, was recruited from Saab to lead the activity. The group was transformed to a regular department in 1968 and Zachrisson became the first professor of Optimization and System Theory in 1969.

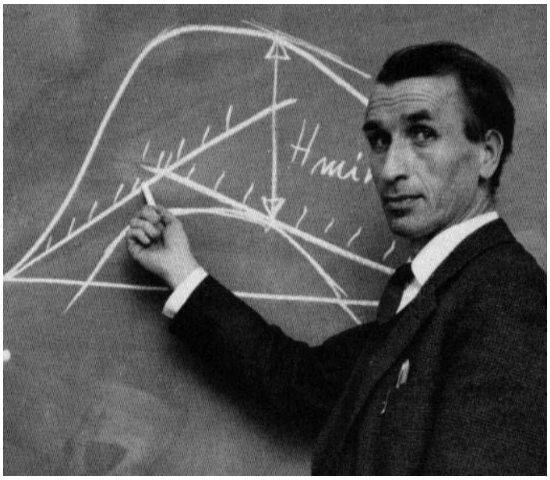

Fig. 3. Lars Erik Zachrisson, the first professor of System Theory and Optimization at KTH. He independently invented proportional navigation and Markov games in his work at FOA and he was a mentor for many of us around KTH with theoretical interests.

4.4. The Theoretical Inertial Navigation Group

In the late 1950s, there was a significant interest in inertial guidance, both for the aircraft Viggen [43] and for missile projects [32]. As the technology was not available, KFF created a Theoretical Inertial Guidance group (Teoretiska Tröghets Navigerings gruppen) led by Prof. Bengt Joel Andersson of KTH and Thorvald Persson of FOA with participation from AGA, Philips, and Saab. Still a student I joined the group in 1955, together with a classmate in Engineering Physics at KTH, Svante Jahnberg. It was a great challenge to participate in the project. It gave us access to much advanced technology. Collaboration with the Instrumentation Laboratory at MIT led by Prof. Charles Draper was a strong stimulation. Prof Winston Markey spent long periods with us. I had the pleasure to be a guide to both Draper and Markey during their visits and I learned much about research during formal and informal meetings with them. The interaction with the Swedish defense industries, and good access to BESK, the only digital computer in Sweden at the time was another attraction.

The inertial navigation systems designed by Draper at MIT consist of gyroscopes and accelerometers on a gimballed servo platform. Position is obtained by integrating the accelerations twice. There will be errors if the accelerometers are not aligned so that their sensitivity axes are orthogonal to the earth's gravity field. The navigation error is proportional to $\omega_0 g t^3$ for large t where g is the acceleration of gravity and ω_0 the gyro drift. In 1923, Schuler [58] discovered that it was possible to reduce the effects of gyro drift in a gyro compass by creating a dynamical system with a natural period of $2\pi\sqrt{R/g}$, where R is the radius of the earth. The period is approximately 84 minutes. Applying Schuler's idea to inertial navigation, it is possible to obtain systems where the error only grows linearly with time for large times. Such schemes are now called Schuler tuning.

The inertial navigation systems designed by Draper at MIT accomplished Schuler tuning by a feedback around the servo gimbals [19,48]. Together with Folke Hector at Philips, I developed a new principle for Schuler tuning using a pendulum whose apparent inertia is increased by feedback from the angular acceleration [5] and [13]. To test the idea, I made a crude mockup based on a conventional vertical gyro, where acceleration feedback was generated mechanically. With this contraption I was able to obtain periods of about 5 minutes. Hector built a more advanced electromechanical system with a rate gyro and electronic feedback. There were considerable scepticisms toward the idea by seasoned control engineers at Philips because the system required very high gain. We started the system, cranked up the gain, and we were indeed able to get the desired period. This experiment convinced me that control was a great field to work in. Having proven that the idea worked, we applied for a patent [12]. Hector's boss Bertil Palme liked the idea and we went to the Philips Nat. Lab. in Eindhoven to apply for research funding. Our proposal was scrutinized by a committee, led by the physicist Prof. Kasimir. We got funding to develop a prototype, which was successfully flight tested [34]. The system was a candidate for the navigation system for the aircraft Viggen and for missiles but KFF and Philips decided to develop a radio-based navigation system for Viggen and the missile RB 330 project was canceled in 1959 [32]. I decided to leave the project in 1961 and move to the emerging field of computer control when IBM had started the Nordic Laboratory in Stockholm. One reason was that work on the guidance systems had made me realize the importance of computers and computing, and IBM seemed like a good place to learn more in these fields.

5. Military Aircrafts

Development and manufacturing of generations of military aircraft of increasing complexity was coordinated by KFF. Saab had traditionally built aircrafts with spaces for black boxes with electronics manufactured by other companies. KFF and Saab had realized that electronics and systems were becoming increasingly important for military aircraft, and Saab got total systems responsibility for the Viggen aircraft project.

Saab had a long experience of fire control. In the 1940s, Erik Wilkenson, a graduate of KTH, had developed a novel bomb-sight. The bomb-sight made a dramatic change of tactics for dive bombing. The sight was essentially an electromechanical analog computer. Key elements were an air-driven gyroscope and a nonlinear function generator. The gyro was manufactured by NAF and the function generator was an asymmetrical rotational body manufactured by Arenco. The bomb-sight was also exported and manufactured in the USA in large numbers under licence [56]. Wilkenson took a leave of absence from Saab for a year and wrote a PhD dissertation at KTH on his work on dive bombing [67].

5.1. R-System

Saab had created a new division called R-systems in 1954, to explore factors that are important for efficiency of military air systems [32]. The group was inspired by RAND corporation in the USA which originally was operated as a project of the Douglas Aircraft Company. The R-systems division was led by Hans Olov Palme, an Aeronautical Engineer from KTH, and an uncle of the former Swedish Prime minister. Palme was an enthusiastic, visionary, and dynamic leader. Talented engineers with a wide range of backgrounds were recruited; many of them later had leading positions in industry and academia. The group quickly became one of the best systems groups in Sweden. It was characterized by strong creativity, a broad range, and deep knowledge. In 1955 the group had about 75 persons [32]. Palme unfortunately had a bad car accident in 1957 and was unable to resume his work. The group continued to strive and many researchers were recruited, among them Zachrisson from FOA. Many new ideas in airborne computers, missile guidance, inertial navigation, simulation, and operations research were generated. The missile RB 330 was one of the projects. Saab got an order for a preliminary system study for a missile with a range of 500–800 km for attacking harbors in the Baltic with a conventional or a nuclear war head. The robot should have an on-board computer and navigation system based on inertial navigation and radio [32,44]. Even if the project was terminated there were considerable spin offs in development of computers and navigation systems.

Fig. 4. The aircraft Viggen. Photo from Saab.

5.2. Embedded Computing – The Central Computer

Saab was a heavy user of the BESK computer and it built a copy called SARA in 1957, [68]. Saab acquired substantial knowledge of computers, which was channeled into the aircraft projects. Saab actually became a full fledged computer company. The computer studies started in the late 1950s for missile applications. Saab had a contract to develop a transistorized computer SANK (Saabs Navigation Computer), which was completed in 1960 [47]. The machine, which was later renamed as D2, had a weight of about 200 kg. A central idea in the Viggen project, motivated by economics, was to have a plane with only one pilot. To enable this it was necessary to automate tasks such as navigation and weapons delivery that earlier had been performed by the copilot. A straw-man for the specification of a flight computer was made in 1960 by Viggo Wentzel and Bengt Jiewertz, [40].

Sjöberg, who had previously worked on missile guidance at KFF followed by two years at AVCO Electronics in Boston, joined R-System in 1960. He explored the possibilities of using a computer in the Viggen aircraft. A fruitful collaboration emerged with the computing groups. Sjöberg developed detailed definitions of functions for primary flight data handling, filtering, gyro platform support, navigation, landing aids, weapon functions, aiming, fire control etc. Jiewertz and Wentzel developed the instruction sets and a computer architecture to support the functions. The possibility of using head-up displays to simplify multitasking for the pilot also emerged. When integrated circuits became available, it appeared that a central computer could indeed be a realistic solution. Sjöberg wrote a report [59] proposing an architecture of the electronic system based on a central, digital computer. The report became known under the ironic name "Fridas visor" (Songs of Frida) after a poem by the well known Swedish poet Birger Sjöberg [40] and [60], indicating that it was a blue-sky idea. The concept of a central computer was considered risky and adventurous, but the idea found strong support. As work progressed, it turned out that it was essential to have support for logic as well as numerics, and efficient one-bit instructions were added. A real-time operating system which permitted loops with different sampling rates (10, 30 and 60 Hz) was developed, [25]. A milestone in the development was a hardware-in-the-loop simulation of computer functions programmed in the D2 computer with input-output signals from an analog simulation of aircraft flight dynamics. The final decision to provide Viggen with a central computer was taken in 1962. For a limited period Saab became the world's biggest consumer of integrated circuits. The central computer in Viggen is an interesting example of a computer whose architecture is matched to a particular control application.

The computer experience that Saab acquired was used for a later version of Viggen AJ 37, which had the first operational digital flight control system. Much later Saab developed JAS Gripen, an airplane that is unstable in certain flight conditions and relies on a digital fly-by-wire system for stabilization. The system uses more than 40 digital computers in its avionic system.

5.3. Complementary Filtering

Military aircrafts are normally well instrumented with sensors for position, velocity, acceleration, orientation angles, and their derivatives. Measurement errors have different nature and it is highly desirable to fuse information from many sensors. The Kalman filter had just appeared when the Viggen project started, but it was limited to linear models while many of the functions in the real problem were nonlinear. A technique called complementary filtering was therefore developed [50, 61]. Complementary filtering is particularly suitable for the three dimensional aircraft motion where it is often necessary to convert variables to different coordinate frames. The particular properties of noise in different sensors can also be accommodated by choosing coordinate systems and transformations properly. For example, the noise affecting distance and angle measurement in a radar are very different. The choice of coordinate system can also have a dramatic influence on the precision and efficiency of the estimates. Computation of sine and cosine can be avoided by exploiting cross products.

Analysis of the filtering schemes was primarily made based on linearized continuous time models. The digital algorithms were implemented using fast sampling. Care was taken when choosing sampling rates for different parts of the algorithms in order to economize on computer performance requirements. When disturbance noise characteristics are known, the filter constants can be determined by least squares. Complementary filtering was used extensively in the Viggen project. Design of the filter requires only the mathematical relations between the different sensor signals. Models of vehicle dynamics are not required for the design. These relations are well defined, and they can be obtained from first principles. The parameters in the relations do not change with flight conditions. It is thus possible to design complementary filters that are robust. The drawback compared with a Kalman filter is that some lead information is lost by not including the control signals in the filter.

6. Academia and International Federation of Automatic Control (IFAC)

The first control course in Sweden was given by professor Donald Campbell from the Servomechanism Laboratory at MIT. Campbell was invited by the Engineering Association in Stockholm to give a course, which was attended by many persons from industry and academia. The first regular academic courses in control were given at KTH in 1949. The lectures were given by Laszlo von Hamos of KFF. von Hamos had arrived in Sweden when a central instrument for fire control was imported from Hungary. Bengt Sjöberg from KFF and Gunnar Attebo of Källe Regulator were teaching assistants. A professorship in control was created at KTH in 1959. Zachrisson and von Hamos were the prime contenders. The faculty preferred Zachrisson and so did many of us younger researchers, but after lobbying by industry, who wanted a practical person, the Department of Education selected von Hamos.

A course in control for electrical engineers was taught by Prof. Henry Wallman in Electrical Engineering at CTH in 1953–1955. He had spent time at MIT, and was the coauthor on the Radiation Laboratory Series book on Vacuum Tube Amplifiers [65]. A professorship at CTH was sponsored by Källeregulator, a regular Department was created and Birger Qvarnström was appointed in 1962.

For a long time, KTH and CTH were the only engineering schools in Sweden. There was a large demand for engineers in the 1950s. KTH therefore started engineering education in collaboration with Asea and Saab. A new engineering school, the LTH, was created in Lund in 1961. Later it became the engineering faculty of Lund University. The first course in control at LTH was given in 1964 by Felix Aasma from CTH. A professorship was created, and I was appointed in 1965.

Sweden participated actively in the creation of IFAC. Both Garde from Asea and Zachrisson from FOA participated in the Cranfield conference in 1951, [29,63]. Laszlo von Hamos signed the IFAC resolution on behalf of Sweden in Heidelberg September 27, 1956. The Swedish participation in IFAC was handled by the Swedish Central Committee for IFAC under the auspices of the Royal Swedish Academy of Engineering Science (IVA). The committe had the same chairman and secretary as the Instrument Society of Sweden (ITF). An attempt to establish a closer collaboration between ITF and the Swedish IFAC committee failed, which was a drawback for both activities. Agerberg presented the only Swedish paper at the First IFAC World Congress in Moscow 1960 [2] and Qvarnström and Persson presented papers at the Second World Congress in Basel [54,57]. In 1964 Sweden arranged the IFAC/IFIP Symposium Digital Computer Applications to Process Control in Stockholm.

7. Conclusions

In Sweden much of the early control developed in industry. University developments came much later. International contacts were very important, and the networks created by a collaboration of universities, industry, and the IVA were essential to get access to relevant technology. Sweden participated in the creation of IFAC but at a fairly modest level. It is a pleasure to see that IFAC participation has accelerated substantially in later years.

I think it is possible to draw some general conclusions from the early development of control in Sweden. One observation is that it is indeed possible for a small country to build an advanced world-class industry by creating a good interaction between industry, governmental agencies, and the international community. Another observation is that systems innovations, where control is an essential part, is at least as important as component innovations. However, systems are more difficult to describe than components. A second observation is that there were good interactions between control and computing in the early period. Typical examples are the IBM-Billerud project and the central computer in Viggen. A third observation is that to have impact on the international scene it is important that the results are disseminated not only in a piecemeal fashion but also that comprehensive presentations of whole areas are given. It is interesting to consider the tremendous impact of the series of books from the Radiation Laboratory at MIT and the classic book by Chestnut and Mayer from General Electric. Some opportunities in high impact books that have been missed are: Asea's development of the frequency response method, the IBM-Billerud project on computer control in the pulp and paper industry, FOA's development of missile guidance, and Saab's development of avionics. It also appears that advances requires groups of critical size, and that development is much stimulated by projects connected to emerging technologies. Even if many good ideas were generated in the industrial projects, it was very beneficial to bring them to academia for completion. I think that participation in demanding projects with hard dead-lines mixed with long periods of free flowing university research is a good way to develop technology.

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