Signal Processing Robotics Using Signals Generated by a Human Head: From Pioneering Works to EEG-Based Emulation of Digital Circuits

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Abstract. This plenary keynote paper describes some pioneering steps in robot evolution, regarding human-robot communication using signals generated by a human head: speech, EEG, and EOG signals. The work was done in 1980's Yugoslavia. Some of the experiments were significantly ahead of time: the 1988 robot control with human EEG was the only such experiment carried out in the 20th century; in the 21st century this research area is increasingly popular. The paper also presents a current research in a new direction in signal processing robotics, the EEG emulation of digital circuits for robot control.

Keywords: Robot evolution · Signal processing · Speech processing for robot control · EEG controlled robots – EOG controlled robots · EEG emulated digital circuits for robot control

1 Introduction

Human-robot interaction explores various ways of communication between humans and robots. This work is devoted to Signal Processing Robotics, which assumes a human-robot communication where an active signal generation from the human side is needed and active signal recognition from the robot side as well. It focuses on signals generated by a human head: speech, EEG, and EOG signals (Fig. 1).

Figure 1 shows a human wearing some kind of hat and/or glasses and/or a microphone, who generates signals which are processed by a co-robot.

This paper points out to some pioneering results in 1980's as well as some current results regarding EEG emulation of digital control circuits for robot control.

The paper has seven chapters. After this introduction, the research context in which this work was carried out is described, the collaboration on robotics in Yugoslavia in 1980's. The next three chapters describe the work on Signal Processing Robotics related to speech (1986), EEG (1988), and EOG (1989). The sixth chapter describes a current direction in EEG based control, the EEG emulation of digital circuits for robot control. The last is a discussion chapter.

A. Rodić and T. Borangiu (eds.), *Advances in Robot Design and Intelligent Control,*
Advances in Intelligent Systems and Computing 540, DOI 10.1007/978-3-319-49058-8_49

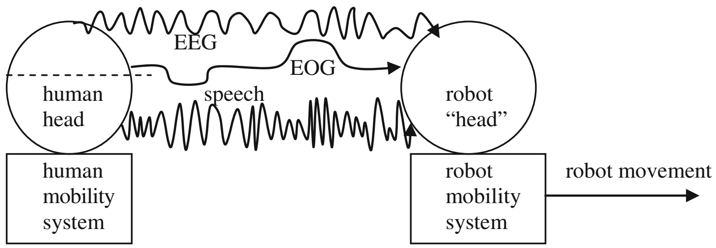

Fig. 1. Signal processing robotics: Actively generated signals from a human head

2 Robotics Collaboration in 1980's Yugoslavia

The 1980's Yugoslavia had several centres where robotics was pursued, with leading centre being Institute Mihajlo Pupin in Belgrade, under the leadership of Dr. Miomir Vukobratovic. The Belgrade School of Robotics [1] has established itself in the robotics research with early works on the robot walking problem [2–7], especially with the 1969 pioneering result on zero moment point [8]. Yugoslavia was a federation of 6 states: Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, and Slovenia. In 1980's the federal government encouraged collaboration between states in the area of advanced technologies and many meetings were held for preparing applications for federal grants. This enabled researchers in robotics to have coordination and understanding of what each research centre was doing. In addition to such collaboration, professor Vukobratovic was organizing symposia and visits to research centres in Moscow and Leningrad. The author of this paper had a privilege to be part of the Yugoslav delegation visiting these research centres. The friendship among Yugoslav researchers developed in these years lasts till today.

Working among other centres, the centre in Skopje had a direction toward using vehicle robots. The first vehicle robot was built 1982 from a toy car, and in 1983 it was controlled by a multitasking software system [9]. In 1984 the scientific foundation of the state of Macedonia approved a project named Adaptive Industrial Robots (AIR), and in 1988 a continuation project named Adaptive Intelligent Industrial Robots (AIIR). In addition to industry applications, the research directions pursued were signal processing robotics and flexible manufacturing systems (FMS) [10]. The results of the project were reported on Yugoslav symposia related to ETAN society, to IEEE societies, and at bilateral symposia in Soviet Union. In the bilateral symposia the Yugoslav robotic delegation presented its state of the art research. In such a context we presented in 1986 our work on genetics and flexible manufacturing systems [11, 12] and in 1989 our work on EEG and EOG head bio signals for robot control, published later in a Russian journal [13].

3 1986: Speech Signal Processing for Robot Control

Although automatic speech synthesis and understanding has been of interest for science and technology since 1930's [14], explicit addressing of speech recognition of isolated words was done in 1950's [15]. In robotics, the first control of a robot using speech commands was demonstrated in 1973 [16] on the humanoid robot Wabot-1 (Waseda robot 1). The next robot named Wabot-2 was built in 1984 as a keyboard music playing robot [17]. However the description given in the literature of both Wabot-1 and Wabot-2 did not cover the speech signal processing, because it was not the most important focus of the Wabot project. The first description of speech processing for robot control was given in a report from the AIR project in 1986. The vehicle robot used was named Adriel-2 (Adaptive Robot of Institute of Electronics). The description of the speech recognition system given in this paper is based on the 1989 report [18] which in turn is based on the project AIR Technical Report done in 1986 [19]. We were interested in Signal Processing Robotics, so for us the actual signal processing was an important part to be described.

3.1 Background Information: Human Speech Signals

Human speech has a distinct frequency spectrum, resembling an attenuating sine wave. The local maxima on the spectrum are named formants. The first formant is around 500 Hz. In the frequency range of a human speech, 0–4 kHz, there are up to 5 formants. There are variations of placement of formants in a frequency spectrum due to individual differences of speakers. Analysis of a human speech is usually performed on a time-frequency chart named spectrogram. The spectrogram actually converts a 1D time signal into a 2D time-frequency image, where gray image intensity corresponds to the power of a time-frequency coordinate.

3.2 System Setup and Hardware Used

The system diagram of our 1986 speech-to-robot interface is shown in Fig. 2. The speech-to-computer interface consisted of a microphone, the signal of which was further amplified by a custom made amplifier. The computer-to-robot interface consisted of power amplifiers needed to drive robot motors, and was custom built in our lab.

The robot Adriel-2-1 used in the experimental work was built in 1984 for demonstration of the gradient following experiments similar to the experiments done by Grey Walter [20], but in a Flexible Manufacturing Systems (FMS) scenario. It was able to avoid obstacles while navigating toward a light source (light bulb). As external sensors it contained two light sensors and two tactile sensors.

The available computer was IBM Series/1 process computer with a module for process control named S4982 Sensor Unit, with 16 analog inputs and 2 analog outputs. The speed of conversion (sampling rate) of its A/D converter was 1500 conversions/s (1500 Hz, sampling time 1/1500 Hz = 0.667 ms). It was not able to process the full spectral range of a human speech (4 kHz), for which the sampling theorem requires

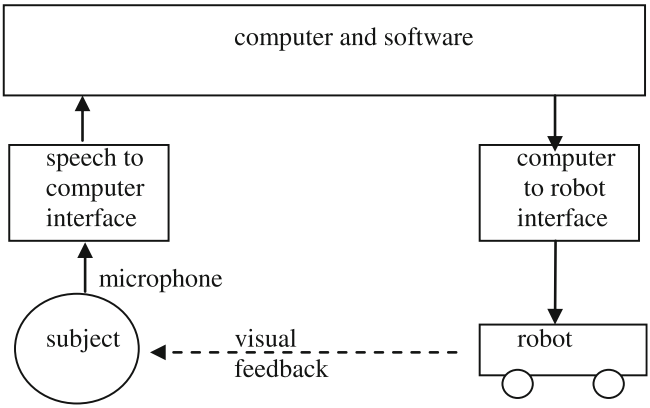

Fig. 2. A system diagram of the 1986 speech-to-robot interface

8 kHz sampling frequency (0.125 ms sampling time). This hardware limitation posed a challenge: develop a speech recognition system based only on the first formant, which for a given speaker can be found in the frequency range between 200 and 800 Hz.

3.3 Speech Signal Segmentation

We used a sound-string representation of a spoken word by which a word in time domain is divided into time elements named word segments. In our case each word contains 40 segments. Each word segment has fixed time duration of 10.67 s, and contains 16 time samples taken 2/3 of a second apart. There are 640 samples per word with the total sampling duration of 426.88 ms, which means that, because of equipment limitations, we take a fixed length sample of 426.88 ms per word. The beginning of a word was recognized automatically, but we did not used recognition of the end of the word. If the word is longer that the 426.88 ms sample it is truncated; if it is shorter it is filled with noise of 800 Hz maximal frequency limited by the input low pass filter.

3.4 Word Spectrogram, Feature Vector, and Robot Command Recognition

On the basis of segment duration, the resolution achieved along the frequency axis is $\Delta f = 1/\tau seg = 93.72$ Hz. Because the number of samples per segment was Nseg = 16, the maximal frequency in the obtained spectrum is fmax = (Nseg/2) Δf = 749.76 Hz. So we obtain 8 frequency bands each of width 93.72 Hz.

The first formant in the *i*-th band is denoted $F1_i$. Since the spectrum frequency components are multiples of Δf, for the value of the first formant we take the order number of the maximal Fourier coefficient C_{ik}, i.e. $F1_i = k \mid k = \max \{C_{ik}\}(0 \leq k \leq 7)$. Figure 3 shows the signal processing in frequency domain.

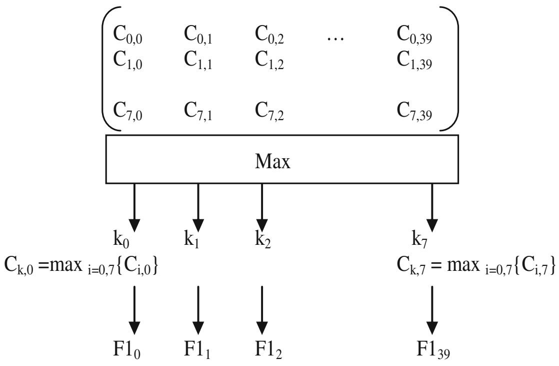

Fig. 3. Signal processing in frequency domain and obtaining feature vector of a word

Once the first formant is found in the spectrum of all the 40 segments, the formant function is determined, F1(iτseg), i = 0, 1, …, 39, which is defined in intervals τseg = 10.67 ms and whose amplitudes are integer numbers from 0 to 7. That way we obtain word patterns of the robot as a 40 dimensional feature vector.

We used 5 word commands in Macedonian language which correspond to commands "start to go", "left" "right", "back" and "stop".

The learning and pattern recognition algorithm is the following:

In the learning process create a vocabulary of 10 versions of the i-th command (i = 1,2,…,5). The command i is represented by the 10 × 40 matrix $Y_i = Y_{i,k,j}$ with k = (1,..,10) word versions and j = (1,..,40) signal features.

In the recognition process, when unknown spoken command **x** appears, then for i, compute all distances between features of **x** and of stored versions in Y_i:

$$d_{ik} = d(\vec{x}, \bar{y}_{ik}) = \sum_{j=1}^{40} (x_j - y_{ikj})^2$$

Then order distances in increasing order and change indexes to obtain

$$d_{i1} \leq d_{i2} \leq \ldots \leq d_{i10}$$

Then compute distance between command **x** and words Y_i as

$$D_i = d_{i1}^2 + \delta \sum_{k=2}^{5} d_{ik}^2$$

where δ is discount factor (in our experiments δ = 0.01), which discounts the sum of the next 4 distances after d_{i1}, the minimal one. Let D is the set D = {D_1, D_2, D_3, D_4, D_5}. Let indmin(.) is index of the minimal value. So, if i = indmin(D) then **x** is recognized as Y_i.

To determine decision threshold, compute next greater minimum distance between **x** and D. Let R1 = D_i = min(D) and let R2 = min{D-D_i}. Then R2 > R1. With (empirically determined) decision threshold $\varepsilon = 1.4$ the decision rule of the algorithm is:

If (R2/R1 > ε AND i = indmin(D)) then **x** is the command i, otherwise undecided. Unclassified command means the robot is not moving and will move on the next recognized command.

3.5 Experiments with Speech Control of a Robot

Among various types of experiments performed [18] containing 3, 4, and 5 spoken words, here we describe experiments with robot guidance avoiding obstacles in which 4 commands in Macedonian language were used, equivalent to "start to go", "left", "right", and "goback". In some experiments the "stop" command is not used because the reaction time is 3 s and recognition of the command "stop" might not finish on time. So the control of the motor forward-backward M1 is pulsed, with pulses of duration 2 s. The robot moves 2 s and then waits for another command, so a separate spoken command "stop" is not needed. Actually, in case of unrecognized command the robot executes the command "stop". This requires repeating the same command several times, which is only practical in environments rich with obstacles. For experimental work we used the room of the Series/1 computer lab, at the Mechanical Engineering Department. The robot was moving on the ground and several boxes were placed such that the subject controlling the robot using speech commands should give various types of commands in order to pass the planned trajectory. Note that the commands "left" and "right" move the wheels left and right and at the time the robot is not moving forward/backward. So the command on motor left/right is separate from the motor forward backward. The performance was 85% correct recognition, 5% incorrect recognition, and 10% unclassified. Usually incorrect recognition was from the command corresponding to "goback".

4 1988: Step in Robot Evolution: Robots Gain Capability of Recognizing Human EEG Messages

In 1988 robotics evolution acquired a new human-robot communication capability, recognition of some features of the electromagnetic energy emanated by a human brain. In that year, the movement of a vehicle robot was controlled by human EEG signals [13, 21–23]. In addition of adding a step in robot evolution, this was a challenge of possibility of solving the problem of psychokinesis, i.e., movement of a physical object with a human's brain power. The engineering solution we implemented was using EEG, which is a manifestation of processes inside a human brain. Let us note that moving robots (or other physical objects) by electromagnetic energy emanated from a human brain is not necessary about reading human thoughts. It is rather self-tuning or tuning a human brain to some mental states which can be translated into EEG features and then recognized by a robot.

4.1 Background Information: Human EEG Signals

EEG (electroencephalogram) signals are electrical signals which can be recorded by electrodes mounted on a human scalp. There are also invasive recordings, with electrodes inside the brain, which with humans are used only in medical needs. In the frequency domain, the EEG signals have range between 0 and 70 Hz, frequencies above that are assumed noise. Some frequency bands have special meanings and applications, for example the 8–13 Hz band named also alpha band (or in time domain, alpha rhythm), or in cases when it is measured from sensorimotor area it is also named mu rhythm. EEG reacts to external events such as sound and visual signals with components named EEG event related potentials. The robot evolution toward “understanding” EEG signals started [21] with recognizing changes of the intensity of EEG alpha rhythm, i.e. the contingent alpha variation (CαV).

4.2 Methods: System Setup and Hardware Used

The EEG based setup used in 1988 was essentially the same as the speech based setup of robot control in 1986, described above. EEG sensors were used instead of microphones, and the EEG-to-computer interface was a biopotential amplifier.

A rack-based biopotential amplifier was designed and ordered for the Adaptive Industrial Robots project. It was custom made by the company Laboratorij Medicinske Elektronike (LME) from Zagreb, Yugoslavia in 1986. After our order of a rack-based system, the company started marketing it as a product named Poly Subcomplet. The maximal amplification was 10 μV/V and the maximal time constant was 10 s. For interfacing the biopotential amplifier with the computer we used a 14-bit A/D converter ADDA14 purchased in Munich, Germany.

The computer used was a PC/XT. The signal processing software extracted features from the EEG and then performed pattern recognition. The pattern recognition required a learning process, in which the computer learned some specific template parameters of a subject, using which the EEG-based commands were recognized.

The robot used was purchased at the Akihabara market in Tokyo, Japan, in 1984. It was a state-of-the-art vehicle robot named Elehobby Line Tracer II of the series Movit robots [24]. It carried own batteries, and had local intelligence to follow a black line drawn on a floor. In our lab the robot had an FMS outfit and played a role of a FMS shuttle robot moving along a closed line drawn on the Robot Polygon.

Robot Polygon was built as a two-floor facility inside our laboratory. Robots (both vehicles and arms) were placed on the first floor which looked like a white ping pong table, while on the second floor, above a human height, a support equipment was placed consisting of computer-to-robot interfaces. Each robot had both power and control lines coming from above, so they do not interfered with the robots movement. The Robot Polygon was the principal part of the Laboratory for Intelligent Machines, Bioinformation Systems, and Systems Software, (LIMBISS) of the Electrical Engineering Department, University Cyril and Methodius.

4.3 Pattern Classification: The Calibration (Learning) Method

A subject can generate increased amplitude of alpha rhythm for example, by closing eyes and relaxing. The relaxation state of the brain is manifested in increase of the energy (amplitude) in the alpha band. A process of calibration of a classifier is needed for a robot to recognize the change of alpha rhythm amplitude. The calibration of the classifier follows the following procedure:

In a 10 s calibration (machine learning) procedure, the subject opens and closes her/his eyes. Since our sampling frequency was 100 Hz, we acquired 1000 samples where from the template parameters will be learned. The biggest problem was what parameters to be learned, since they should be fast computable. It needed a procedure that reads EEG sample, computes the parameters, compares them to learned baseline parameters, and sends command to the robot, all that in less than 10 ms on a PC/XT in the year 1988.

The learned parameters were chosen to be both changes of EEG amplitude and changes of time intervals between EEG amplitudes. They are fast computable since it needs comparison only with the previous sample to obtain the changes. So the learning process scans the 1000 EEG samples and looks for local extremes, hills and valleys of the signal, the points where gradient changes the sign. For each hill, its amplitude is determined relative to the previous valley from where the hill started to rise. Also for each hill the width of the hill is determined as time distance between the bottom of the hill and the top of the hill. More details are given in [25].

4.4 Pattern Classification: Probability Distributions and Decision Threshold

Both obtained amplitude differences and time differences are counted and placed in corresponding probability density distributions. So each subject was represented by a pair of distributions, EEG amplitude difference p(A) and EEG time difference p(T). Due to mental states of relaxation (closed eyes) and attention (open eyes) the distributions have corresponding shift. The distributions overlap, so there are possibilities of false positive and false negative decisions. Decision thresholds should be determined empirically for each parameter. Let $\theta_{\Delta TO}$ be the threshold for eyes open and $\theta_{\Delta TC}$ be the threshold for eyes closed for a particular subject obtained during the calibration process. Between each EEG sample we obtain two values ΔT and ΔA, and the areas of distributions

$$\Delta T < \theta_{\Delta TO} \text{ and } \Delta T > \theta_{\Delta TC}, \text{ as well as } \Delta A < \theta_{\Delta AO} \text{ and } \Delta A > \theta_{\Delta AC},$$

where a minimum number of false decisions are made. The decision could be made on the basis of amplitude distribution only, but we included time distribution for improved accuracy. We also used confirmation sequence of three samples in a row, meaning that in each sample its amplitude difference and time difference should be greater than $\theta\Delta A$ respectively. So the simplest computation was

$$\text{if } (\Delta A(t) > \theta_{\Delta AC}) \text{ for three consecutive times}$$
$$\text{then (mental state = relaxation) do (robot = resume movement)}$$

4.5 Demonstration Experiments

The demonstration task consisted of a shuttle robot following a closed trajectory on a "factory" floor. The trajectory contains "stations" where the robot should stop. The task of a human operator is to stop the robot at a particular "station" and after a pause, to resume the robot movement. The initial behaviour of the robot is "move along the line". The subject observes the distance from a "station" S and closes the eyes and relaxes so that the robot moves toward S. Ideally, the subject opens the eyes before S is reached and stops the robot at S.

Six subjects were involved in the experiments. The needed training and examination time for a subject was in average 30 min. After that a subject was able to stop and move the robot with 70% accuracy. Two subjects were engaged in the task to follow the movement of the robot along the trajectory and stop it at particular points (stations) along the trajectory, and both were able to complete the task.

Let us note our 1988 work on human EEG based robot control was the only such work reported in the 20^{th} century. In the 21^{st} century there are many robots controlled by EEG and the research in this area is progressing.

5 1989: Step in Robot Evolution: Robots Gain Capability of Recognizing Human EOG Signals

In 1989 the project AIIR made a next step in controlling robots using signals generated by a human head. The signals generated by moving human eyes, electrooculogram (EOG), were used to control the movement of a vehicle robot. The robot used for this task was the Adriel-1 robot, the first robot built in our lab, even before the project AIR was approved. However inside AIR projects this robot obtained its FMS outfit. Adriel-1 robot had both body sensors and inside sensors. Body sensors were whiskers placed in front left side and back. Internal sensors were wheel sensors and timer sensor. It was a "wheels and whiskers" type robot, the classification used by Margaret Boden [26] in the description of robots built by Grey Walter [20]. The robot commands for Adriel 1 were: MoveForward (MoveBackward) for a timer value, MoveLeft (MoveRight) for angle step, and Stop.

The robot Adriel-1 was built in 1982 to solve the problem finding a goal ("orb", or exit) in a simple labyrinth, using wall following method. The "orb" was recognized by a voltage value sensed by front whiskers. Besides being the first robot driven by EOG signals in robotic evolution, to the best of our knowledge it was the first robot driven by parallel programming (multithreading) software [9]. The programming was done in Event Driven Language (EDL) of the Event Driven Executive (EDX) multitasking operating system of the IBM Series/1 computer.

The EOG setup is very similar to the EEG setup. Usually four EOG electrodes are needed for determining the gaze, direction where eyes are pointing; one pair is for horizontal movement and the other is for vertical movement. We used three electrodes: one in the middle between the eyes and two below both eyes. The eyes movements used were: up (robot move forward), down (move backward), left (move left), right (move right), and wink several times (robot stop). The experiments with this robot were simple trajectories with moving left and right.

6 EEG Emulation of Digital Circuits for Robot Control

This chapter describes a state of the art work in robot control, the EEG emulation of digital circuits for robot control. The description here is part of a recent, more detailed report [27].

Control circuits for robot control contain standard elementary control devices, e.g. [28, 29]. For example, the most frequently used elementary control device is a control switch. Among other examples of elementary control devices are flip-flops (state determiners) and demultiplexers (serial to parallel converters). The idea of this research is to emulate some robot control devices in processes generating EEG signals.

6.1 EEG Emulated Switch and Control of a Robot

A switch is a necessary element of any control and usually activates or stops some activity, possibly after some other activity. The process of pattern recognition usually implements a switch announcing the event that a pattern has been recognized and appropriate action should be taken. Some kind of EEG switch was inherently used in control of objects since the challenge of brain-computer interface (BCI) which was made by [30]. All the three following experimental BCI works [21, 31, 32] controlled an object using EEG; however an EEG emulated switch was first time explicitly shown in the control of a robot in an application [21, 22]. An increased alpha activity activates an EEG emulated switch which controls stop/resume movements of a shuttle robot along a closed line.

6.2 EEG Emulated Flip-Flop

The EEG emulated flip-flop was first used in a work on CNV controlled buzzer [33, 34]. The open-loop CNV paradigm was proposed in [35] and the challenge of CNV based BCI was stated in [30] The closed loop paradigm remains state Q (expectancy present) after CNV is established, but then disables the S2 signal of the paradigm. That makes CNV to degrade and a new state is now established, noQ, meaning expectation state absent. Then S2 stimulus is activated again, and so on, the brain with its expectation state emulates a flip-flop which is shown manifested by its CNV potential. The CNV flip flop was used to control two robotic arms to cooperatively solve the Tower of Hanoi problem [36].

6.3 EEG Emulated Demultiplexer

The EEG emulated demultiplexer is a control device which is able to extract two or more commands from a single EEG channel. This allows the use of inexpensive applications in which several robot behaviours are controlled by a single EEG channel. An EEG epoch in a trial is divided into information frames. In other words, the EEG sentence is parsed into EEG words. Each word contains information for demultiplexer decoders. The address decoder will activate an output command channel, and the command decoder will send command through the opened output channel. The proof of the concept was given by controlling two motors of a robot arm to move to a target area avoiding an obstacle along the way [27]. The current experiments in this direction are carried out in both the laboratories of Robotics and Embodied Intelligence Center of South Carolina State University.

6.4 EEG Emulated Modem

The dominant view in BCI since its onset [30] is that EEG in its nature is a random signal. BCI approaches usually compute EEG amplitude as a variance of a random signal. Our work [21] points out that EEG can be viewed as a broadband carrier of messages. A carrier frequency band (e.g. alpha band) carries a message modulated in its amplitude. So the idea is that human robot-interaction using EEG can be viewed as a modulator-demodulator (modem) system in which a human wants to send a message m (t) and it modulates the carrier EEGband(t) for example alpha band. So the message sent is m(t)EEGband(t). The robot receives that message and demodulates the signal obtaining the message m(t) and carries a command encoded in that message.

7 Discussion: Signal Processing Robotics and Robot Evolution

The discussion can be summarized based on Fig. 1 shown in the Introduction section. It is a modification of the figure shown in a book on robotics [37] where Signal Processing Robotics was introduced as a separate chapter.

Among many directions in robotic evolution, humanoid robots (both legged and R2D2 type) are a research area of significant interest, which can be traced back in history, but it seems the first designed humanoid robot was Wabot 1 [16]. It should be noted that in robot evolution one important part is the evolution of biped robots, which happened before Wabot 1. In biped robot evolution Vukobratovic and his team from Mihajlo Pupin Institute has a very important role influencing the subsequent research on biped and humanoid robots, including the work of Kato and his team [38]. Kato and his group added speech communication feature to the 1973 robot Wabot-1 (walking humanoid) and the 1984 robot Wabot-2 (keyboard playing humanoid) [17, 39]. In addition to the direction of humanoid robots, other types of robots - vehicle robots are of current interest, including self-driving cars [40], automatic guided vehicles (AGVs), and Mars rovers, among others. Although this evolution started back in history too, the first vehicle robot was designed by Grey Walter in 1950 [20]. Such robots were used as an approach to psychology named synthetic psychology, in the book indeed named "Vehicles" [41].

Working with vehicle robots, we achieved some pioneering results in robotics, such as multitasking software architecture for robot control in 1983, description of signal processing for robot control using speech commands in 1986, EEG control of a robot in 1988, and EOG control of a robot in 1989. This paper described the part of Signal Processing Robotics as applied to speech, EEG, and EOG commands for a robot.

Additional work, which started in 1985 [42] was done in relation between flexible manufacturing systems and genetic engineering. The collaboration in 1980's Yugoslavia was an important factor in the effort and presentation of the pioneering results described in this paper.

Acknowledgement. The work described here was funded in part by Macedonian Association for Scientific Activities under the grant Nr 090110384 for the period 1984–1987 and from the Macedonian Ministry of Science under grant Nr 08-778 for the period 1989–1992. Part of this work was funded by United States NSF grant Nr 0447660 ext 2005-701 for the period 2005–2008.

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