

Electroencephalogram-based Brain-Computer Interface for Internet of Robotic Things

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Abstract Nowadays, Internet of Things (IoT) devices are developing rapidly, as well as the new approach based on IoT technology is Internet of Robotic Things (IoRT), which significantly expands development fields of robotics. Although automatization of cooperating objects in the IoT system is getting more-and-more solved, in some security-critical cases, human intervention is inevitable. In the article, a Human-Machine Interface (HMI), enabling human-machine interaction has been achieved, by using Electroencephalogram (EEG) based brain-computer interfaces (BCI). By applying the worked-out BCI system, a test environment has been assembled, where latency of human intervention has been analyzed.

1 Introduction

By the development of informatics, such new ways appeared, which may also play a major role in the future development of robotics. One of these ways is the Internet of Things (IoT), which concept has become usual since the beginning of the 21st century, and is rapidly developing. [1]. IoT gives the possibility for lots of uniquely addressable things to communicate and exchange information with each other over the existing network systems and protocols. [2, 3, 4] IoT, as a concept, was introduced formally in 2005, in the ITU Internet Reports of the International Telecommunication Union (ITU). [5] The IoT enables to make information detected by these objects transmittable, and the objects themselves controllable, by using the current network infrastructure. [6, 7] This provides the opportunity to integrate the physical

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world and IT systems in an even greater scale, which leads to the enhancement of efficiency, accuracy and economics by minimal human intervention. This concept appears regarding the Ipar (Industry) 4.0, which is based on the formerly mentioned cyber-physical systems. [8, 9].

1.1 Internet of Robotic Things

The IoT technology provides several possibilities for expanding opportunities of robots, and recognizing this, ABI Research has created and introduced the Internet of Robotics Things (IoRT) expression in its Report of 2014. [10] The Internet of Robotic Things is a new concept for supporting robotic systems including industrial, home robots or other complex automatic systems with humanlike skills, where partly autonomous systems can communicate with each other and use ad-hoc, local, distributed or cloud service based intelligence to optimize acts and motions in the physical world taking into account several factors for example cooperative, flexible, safety, production, logistics aspects using information exchange, data sharing.

When the information scanned by the robot is not adequate for the optimal operation the robot can collect additional information from the environment and/or can use additional cloud services to determine the appropriate action. To achieve these functionality several technology has to be applied based on the knowledge of robotics, mechatronics, cyber-physics, artificial intelligence, bio-engineering, information exchange network or cooperation. Fig.1

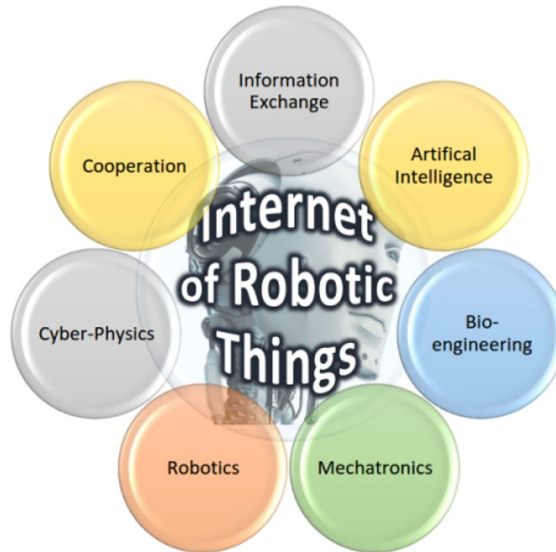
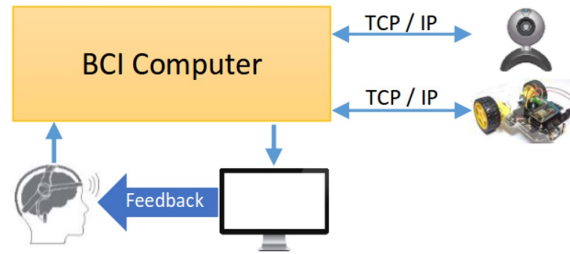


Fig. 1 Knowledge base of Internet of Robotics Things

Fig. 2 Knowledge base of Internet of Robotics Things



The IoRT concept dealing with the extension, new business, and investment opportunities of IoT and robotic devices to provide advanced, adaptive, more intelligent, collaborative, heterogeneous robotic capabilities using the technologies, among others, Networked Robots, Cloud Robotics, Robot as a service. In order to achieve the mentioned aims a number of important aspects has to be considered as standardization, interoperability, common architecture/infrastructure design including time-varying network latency and security for example.

In the IoRT system, the robot is integrated into the smart environment. IoT technology, communication of cooperating robots, equipment gives a great help to automate and optimize these systems, but in several, for instance security-critical cases, human supervisory of these systems needs to be ensured. Human-Machine Interfaces (HMI) enabling communication between IT-systems and humans are emphasized, in which field there are many researches in progress, such as processes based on observation of gestures, eye moves or brain activity. There are several methods available for brain activity, but in terms of mobility and price, the application of Electroencephalogram (EEG) based devices worn on the head promises the most opportunities. EEG device measuring human brain activity was invented by Hans Berger in 1929, searching for the answer by using this device, what kind of connections can be shown between differential psychological and physiological conditions. [11] This technique has been becoming smarter in the past decades, and several changes occurring during the activity of different brain lesions have been observed. By today, this technology has enabled the design of mobile headsets capable of registering EEG signals. The brain-computer interface (BCI) is one of the most rapidly developing multidisciplinary research fields nowadays.

BCI system, which can transmit different information (commands) based on brain activity by processing signals arriving from the human brain, creates a channel between the brain and an external device (for example a mobile robot). The goal of the first BCI researches was to enhance life quality of patients suffering from different neurological disorders. [12, 13] But by nowadays, research fields embrace several other application fields, such as the application of control features. BCI systems based on the operation of EEG type devices, have a relatively simple design, they are portable, safe, and their operation are also quite simple. [12, 13, 14, 15, 16, 17]

The article examines the design opportunity of supervisory achieved by moving of mobile robot applying IoT technology via brain-computer interface, which can utilize some cognitive human skills and features by a BCI system. (Fig.2)

To design a brain-computer interface system, a headset applying a cost-efficient EEG biosensor, and a self-built mobile robot have been used. In the testing environment built-up by the help of these devices, users brain activity is examined by an EEG headset, which transmits data to a computer for process and analyzation purposes. BCI application running on the computer controls the speed of a WiFi mobile robot according to the processed information, and enables remote observation of the robot through a web camera. The article examines interventional latency in the created testing environment in that case, when the user can directly see the mobile robot, and when the robot is observed through a web camera, while the speed of the robot can be influenced by changing attention.

2 Theoretical background of EEG based Brain Computer Interfaces

Human brain activity induces minor voltage changes, which can be measured on the head skin, and these information may be registered by Electroencephalogram devices. The registered signals can be interpretable by the BCI, which can be transformed to command lines.

2.1 Role of PFC in controlling concentration strength

Human brain is the highest level (conscious) nerve operational field, which, contrary to the common belief, is not a general computer equipped with a central processing unit, rather a complex collection of competing sub-systems, whereas these very specialized sub-systems are responsible for unique tasks. [18]

Frontal lobe of human brain is responsible for several duties. Among others, it controls conscious moves, and our thinking and social behaviour are also managed by it. It also plays a major role in problem solving, planning, speaking and controlling of skeletal muscles. The very first part of the lobe is called Prefrontal Cortex - PFC), which is the control centre of our brain, furthermore, nerves enter to the lobe from all of our senses, and this region is responsible for creating of concentration abilities. [19, 20, 21, 22].

During anatomical examination of the brain, it has been proved, that frontal lobe consists of the primer motoric lobe, and the PFC in front of it, in which venter and dorsum regions responsible for different functionalities can be observed. [23, 24, 25] The biological complex role of PFC is presented by multiple exchange connections between fore-brain and brain-stem [24, 25, 26], furthermore, it plays a key role in such cognitive processes, like ongoing maintenance of attention, learning, remembering, and autonomous operations, so PFC regions are significant in controlling the strength of concentration. [27, 28, 29, 30, 31, 32, 33, 34, 35] Fig.3 shows the

location of PFC in the frontal lobe, and its brain regions responsible for different functions.

From the Figure, the following three functions can be read: attention, emotional reaction, behavior and decision making, furthermore, the location of brain regions responsible for these functions are also visible. Among these areas, regarding brain-computer interface, for achieving the goals of profession, attention is the most important. For examination of attention, among the later presented measuring areas, the so-called Frontopolar1 (Fp1) position is the most suitable, which is an important perspective regarding the system to be established.

It has been observed, that such patients, who had got damaged PFC, were hardly, or even not able to learn new knowledges, adapt to different tasks, solve problems, or execute tasks requiring high-level concentration. [27, 28, 36] PFC, beside controlling of the value of attention, plays a major role in the optimal operation of work memory, while for temporary store of sensor information, and for connecting reactions on external stimuli, flawless operation of PFC is inevitable. [37, 38]

For monitoring human brains PFC activity, several technologies are applied, primary in medical and laboratory environment, such as Computed [Axial] Tomography (CT), Magnetic Resonance Imaging (MRI), Functional Magnetic Resonance Imaging (fMRI), Single Photon Emission Tomography (SPECT), Proton Emission Tomography (PET), and Electroencephalography (EEG). [39, 40, 41, 42, 43]

The above listed, different imaging devices provide quite accurate image about the structural and functional operation of the brain, their application regarding activities of moves are limited. By the development of EEG devices, mobile EEG based devices worn on the head have become available, which depending on the number of sensors, give image about functional operation of each areas of the brain. [44] Wear of such designed EEG based headsets is not too inconvenient even after longer period of time, so it can be applied not only in laboratory environment, but also in everyday use.

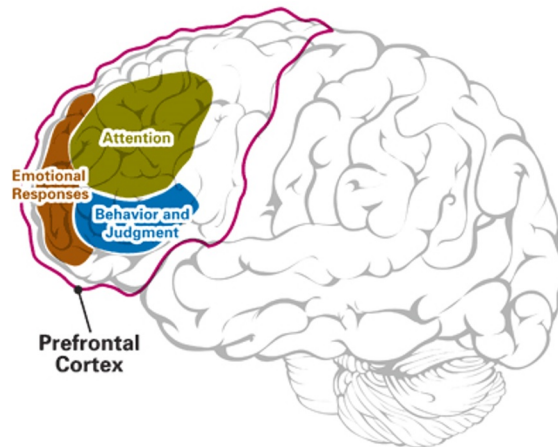


Fig. 3 The role in PFC area in each functions.

2.2 EEG registering and signal processing devices of BCI systems

Registration of EEG signals can be categorized according to several methods, such as invasive and non-invasive processing methods. If the detector sensor is placed inside the human skull, in the brain tissue, then we are talking about invasive process, whose benefit is that high-frequency components can be measured much clearer and more accurate, but due to health risks and several ethical aspects, they are primary used in animal experiments. In case of non-invasive method, electrodes are placed outside the skull, according to the 10-20 international standard (Fig.4). This application method is much more likely used on humans, because it does not endanger them due to the implantation, but it has the disadvantage, that the measured signals are noisier. [45, 46, 47]

In the past years, several EEG headset have been developed not only for medical use, which operated from own batteries in order to ensure mobile use. Now some widespread EEG headset is being introduced, which are also suitable for achieving unique-developed BCI.

2.2.1 Neurosky MindWave Mobile

The MindWave Mobile EEG headset (Fig.5) is the development of Neurosky. Several universities cooperated in the development of NeuroSky ThinkGear EEG technology, such as Stanford, Carnegie Mellon, University of Washington, University of Wollongong and the Trinity College. In the device, dry EEG sensor made of stainless alloy is applied in Fp1 position, and a reference sensor, by a detector connecting to the earlobe. The device transmits pre-processed data through Bluetooth wireless

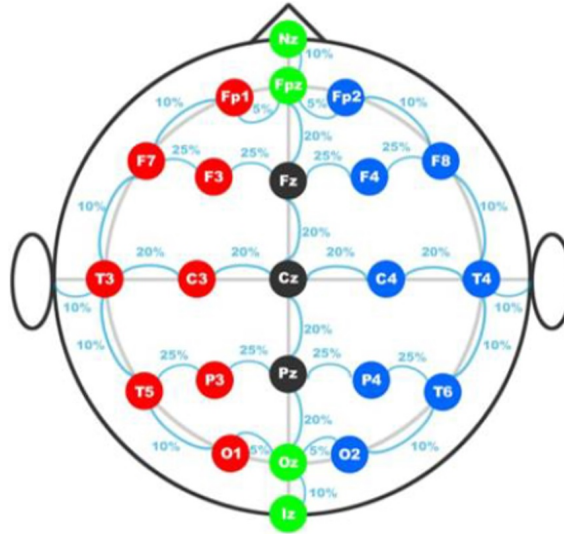


Fig. 4 The International 10-20 standard, Fp1 measurement position relevant for the research is well-shown on the left of the frontal lobe.



Fig. 5 MindWave EEG headset

connection. EEG signals are sampled with 512 Hz frequency, and digitalizes with a 12 bit A/D converter. [48, 49] The device, thanks to ThinkGear technology is suitable for defining the value of attention [48, 49], this value is used in the examinations.

3 IoRT ready Mobil Robot

The mobile robot is a self-made unit assembled from main parts capable of WiFi wireless communication, which enables easy attachment with virtually all computer based control units, and even achievement of IoRT functionality.

3.1 Design of the Mobile robots hardware

At the design of the mobile robot, simple design, upgrade-ability, and IoT based on wireless communications were the main aspects. To achieve the experiments, simple control feature, the speed control had to be ensured. In case of the mobile robot, the module based on ESP8266 chip manufactured by Espressif Systems was chosen, in which the micro controller and a WiFi communication unit was achieved in an integrated circuit.

The device is available in severally designed modules, for development purposes, the ESP-12E containing integrated aerial making important outputs of the circuit available was chosen. To the module, a 2nd generation LoLin developer chip was chosen, which contains the 3.3V voltage regulator required for mains supply via USB port, and the USB-UART serial converter based on CH340G circuit, required for programming via USB port was chosen. Connection of other external modules to the LoLin developer chip is supported by a separate I/O module. (Fig.6).

For the purpose of the mobile robot, primary the simple design, however universally applicable design providing upgrade-ability, enabling chassis moving mechanism was preferred. Regarding the moving mechanism, the two driven front wheels

and one free rear wheel design was preferred. The mobile robot kit contains a removable surfaced, transparent plexi chassis, two driven wheels, an engine unit containing two 1:48 gear direct current motors, and other supplements required for assembly.

For driving the direct current motors, a module based on L9110S motor controller circuit was chosen. In the front of the robot, three distance detectors were attached to detect the environment and avoid collisions. The mobile robot containing the assembled modules placed on the chassis, and the motor and mains inputs are shown on (Fig.7).

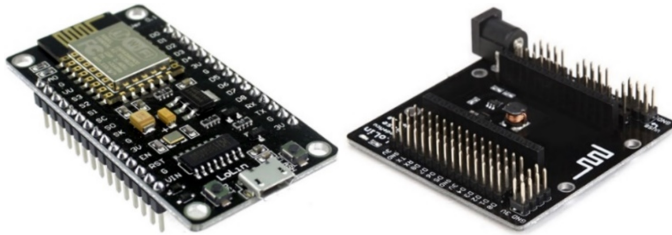


Fig. 6 LoLin ESP8266 developer chip and I/O adapter module

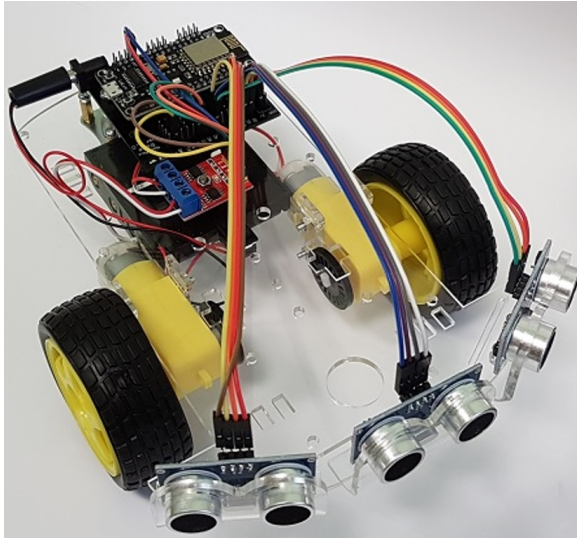


Fig. 7 Assembled mobile robot

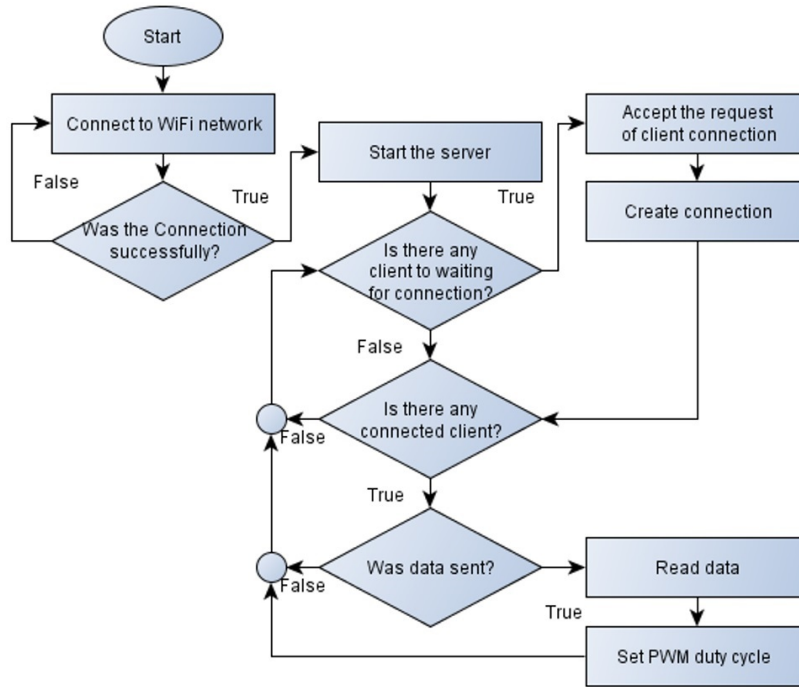


Fig. 8 Flow-chart of the program enabling speed control of the mobile robot

3.2 Design of Mobile robots software

For ESP8266 micro-controller capable of WiFi communication, several development environments are available, such as the Arduino development environment. For programming the developer chip, driver for CH340G integrated circuit enabling USB-UART connection shall be installed, which creates a virtual serial port on the computer. Programming of WiFi communication connection is supported by the ESP8266WIFI function library. The BCI system sends the data varying between 0... 100, defining the mobile robots speed, to the mobile robots controller unit, joining as a client to the server via TCP/IP connection. Flow-chart of the program enabling speed control of the mobile robot is shown on (Fig.8).

4 Implementation of the software of BCI-based system

For managing data measured by the MindWave EEG headset, such a software is required, which is able to process the detected brain bioelectric signals in real time, at the site of the measurement, and also enables the graphical visualization of these information, and their storage for posterior processes.

The software, beside process of EEG signals, is suitable for visualization of a remote IP camera, and by its support, nevertheless the location, enables the observation of the move of a mobile robot, and also allows the definition of latencies related to the control of the robot.

4.1 Planning of BCI-based system

In the so-called overview phase of the development, different aspects of the BCI-based testing system, and its connections have been revealed. Beside that, structural design of the system has been defined, elements participating in the structures and their communication technologies, as well as their transmit media.

4.1.1 Components of BCI-based system

Following the measurement, digitalization, pre-process, normalization, filtering of bioelectrical signals coming from the brain activity, primary the time periodic and/or frequency range features of EEG signals are performed. According to the features of the EEG signal, classification of signals is performed, which information may be displayed, or by their utilization, even further functions can be achieved, such as speed control of a remote mobile robot using TCP/IP connection, and the display of the online screen of an IP camera, which means a feedback for the user regarding the move of the robot. Components of the BCI-based system are shown on (Fig.9).

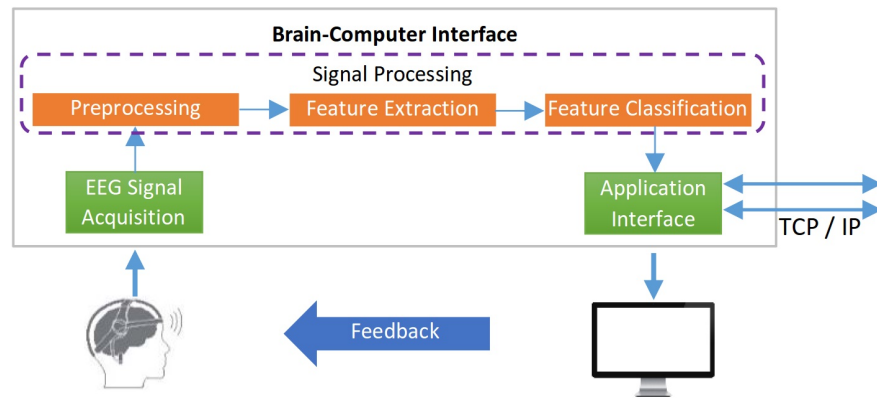


Fig. 9 Components of a BCI-based system

4.2 *System design*

During the system design, software structures, data structures and algorithm descriptions to be implemented have been defined. During the planning of the program, some implementation alternatives have been revealed in an iterative way, and accordingly, the most proper implementation has been chosen, and continuous reviews have been made for improving earlier plans. During the planning, the logical plan of the system has been created, as well as the static, dynamic and case models, which provide the main part of the systems implementation.

During the implementation of the application, implementation techniques written in Martin, Robert C.: Clean Code Handbook of Agile Software Craftsmanship book have been utilized, making source codes easier to read, improve and maintain. During the implementation of functions, the one responsibility principle has been used, which says, that a function shall be responsible for only one task, this way evading the long source code logic (which is sometimes hard to follow).

4.2.1 Main logical plan of BCI system software

(Fig.10) describes the main logical plan of the implemented system by a flow-chart, so displaying the systems logic. On the flow-chart, main steps of the programs operation are well-shown; data process, data communication required for speed control of the mobile robot, and data storage have been implemented in the line 1.

4.2.2 Planning of use case model (users view)

Beside the static and dynamic views, I think that users view design is also inevitable. According to the model, we may reveal, who the system provides services for, who may be persons, systems, or even other programs. From users point of view, by defining actors and tasks, it shows the behaviour and functionality of the system, this way achieving the examination of some use cases. Fig.11 shows a simplified user case of the BCI-based IoRT System.

4.2.3 Planning of the static model (designs view)

Following the overview of the logical operation of the BCI application, the installation view of the application has become actual. Such planning is significantly supported by UML (Unified Modelling Language) modelling language providing visualization, which helps to create such diagrams, which represent a group of static elements. From the static diagrams available in the UML (Class, Object, Component and Deployment), more have been used. From the static figures of the application to be implemented, a simplified class diagram has been chosen, where each planned classes and connections between them can be observed (Fig.12). Due to boundary

reasons, on the figure, in case of some larger class diagrams, data tags and tag functions have been removed.

4.2.4 Planning of dynamic model (operational view)

Different object status changes and co-operations can be defined in dynamic model, so creating the operational view of the application. During the dynamic planning, among dynamic diagrams available in UML (such as Sequence, Activity, Information Flow and Communication diagram), more have been applied. From the dynamic figures of the application to be implemented, a simplified sequence has been illustrated (Fig.13), where time-line of message exchanges between each objects can be observed.

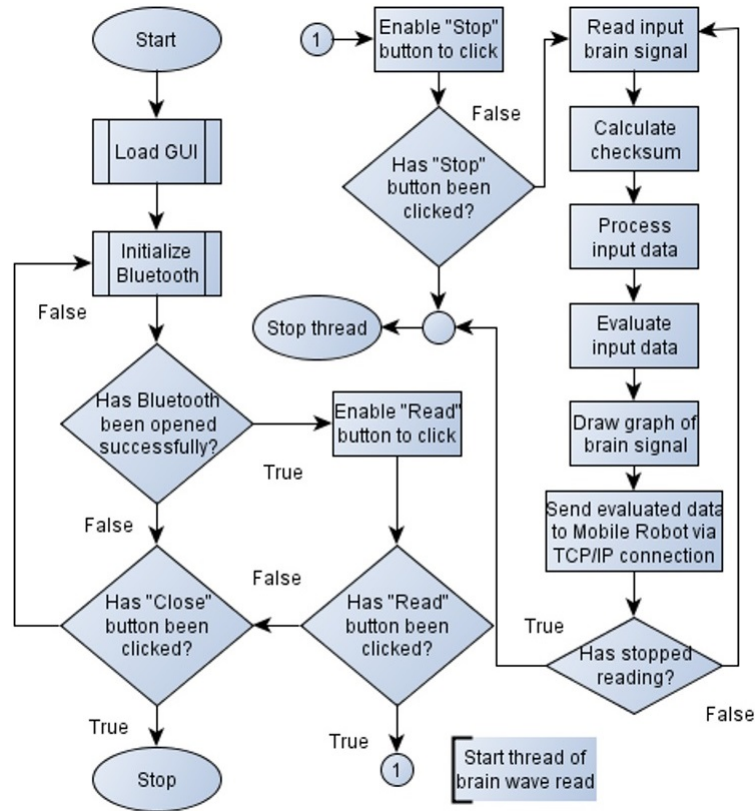


Fig. 10 Overview of logical plan of BCI system software

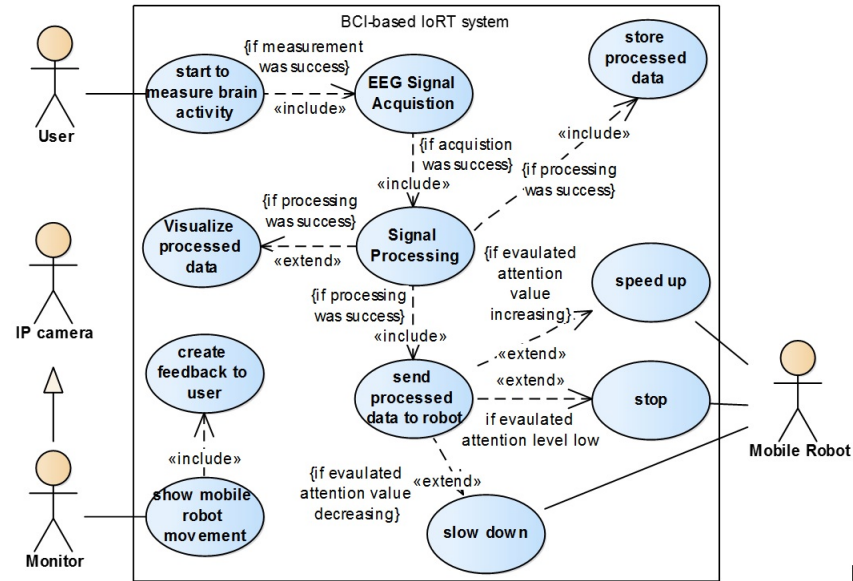


Fig. 11 Simplified use case diagram of the application

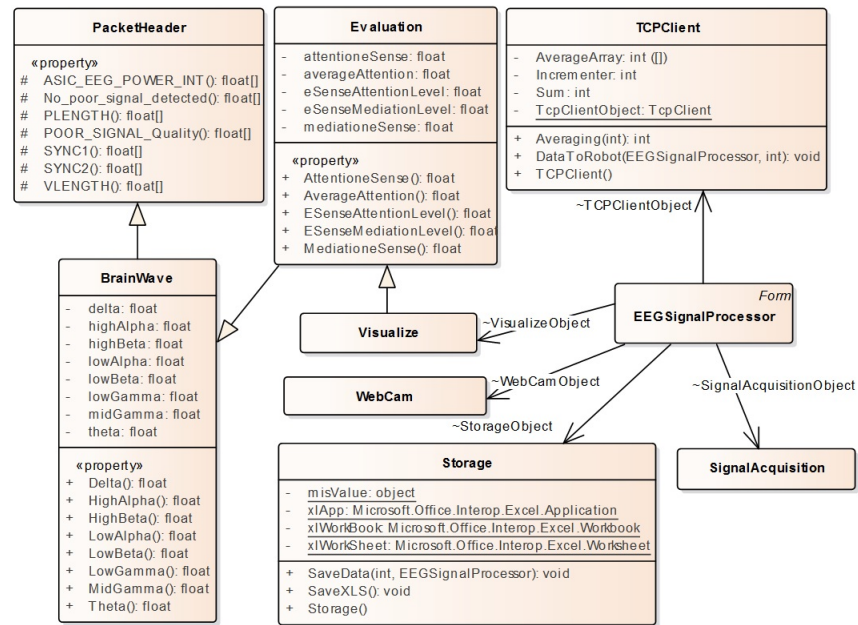


Fig. 12 Class diagram of the prospective application

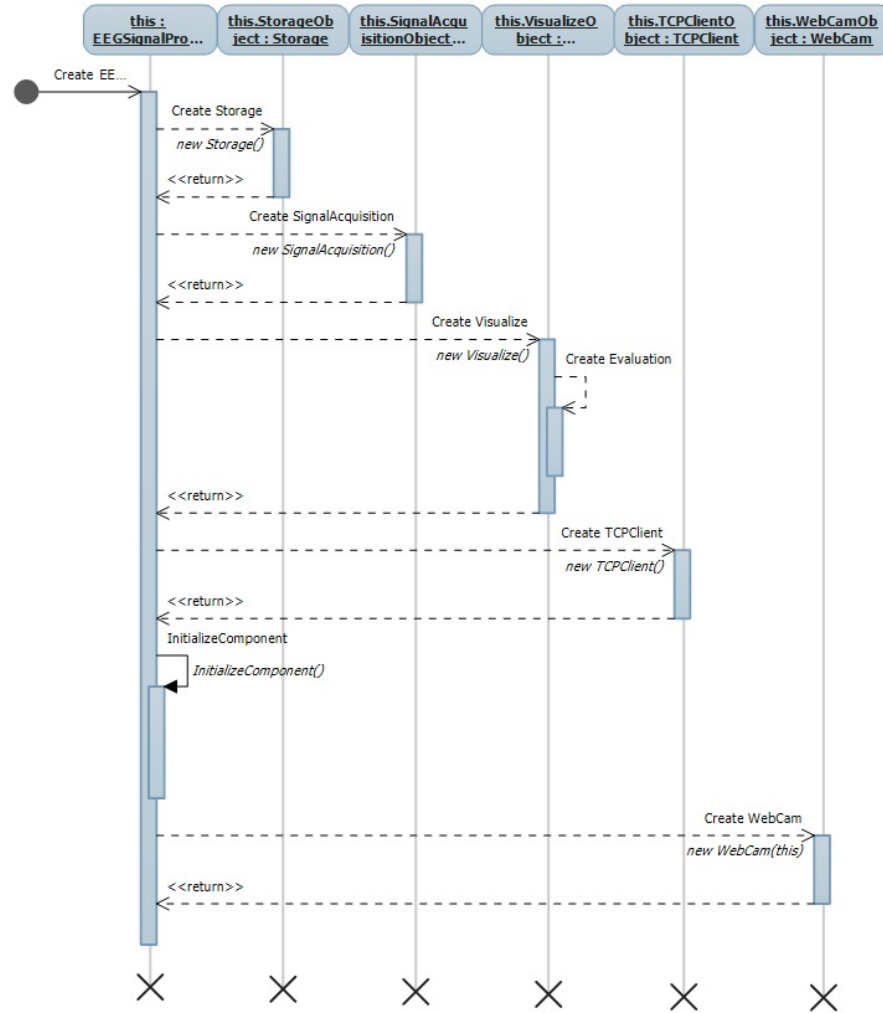


Fig. 13 Sequence diagram of prospective applications EEGSignalProcessor class constructor

5 Results

The software of the BCI-based IoRT system is applied, upon the planning models introduced in the previous sub-chapter. Examining the class diagram of the static model, the application can be divided into 9, well-defined type descriptions, most of them are described by associative or inheritance connection. Now the BCI interface capable of supervising the developed IoRT devices, the testing environment required for the examination of BCI interface latency, and the results of the examination have been introduced.

5.1 BCI control for IoRT devices

The implemented application, such as the BCI interface, achieves the suiting of EEG headset, the process of information sent by the headset, their presentation, and the control of devices capable of remote communication via TCP/IP protocol, as well as the monitoring of the process via a web camera. The application is capable of simultaneous presentation of several processed information, displaying both the actual values of brain wave strengths defined by the spectrum-analysis of brain bio-electrical signals, and their changes by time. This way built-up system achieves the evaluation of some cognitive factors, like attention level, by using the strength of brain waves defined by brain activity.

Following the throughout study of dynamic planning models, the application may be divided into five main function parts: data process, display of processed data, forwarding required data for the mobile robot, storage of processed data, and the display of the IP cameras view for the user. The data processing unit performs the reading, conversion and process of data sent by the EEG headset via wireless communication, while the data display unit performs the display of defined signals, by a pre-defined bar graph and timing diagram. Forwarding of evaluated data to the mobile robot, and the display of the IP cameras view have been performed by applying TCP/IP protocol. Evaluated and processed data have been stored in a pre-defined structure. Fig.14 shows the applications user interface during operation.

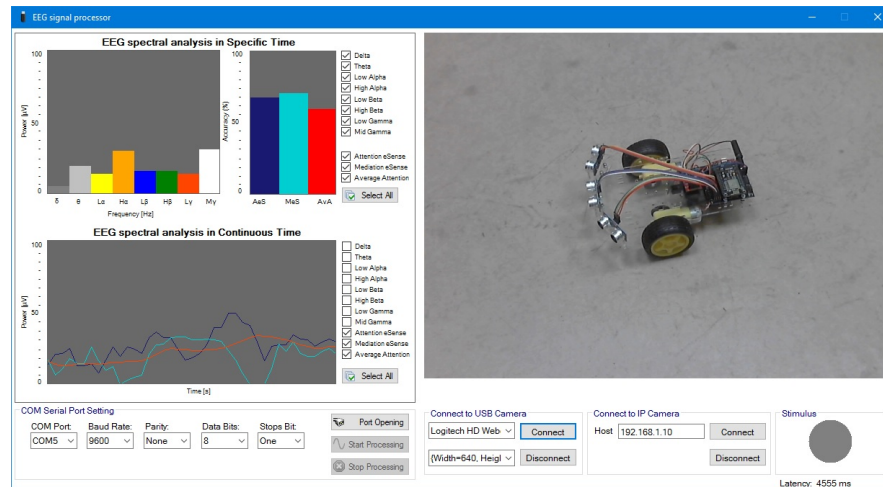


Fig. 14 Graphical user interface of BCI system software

5.2 Test environment for BCI based IoRT control

For testing the control of BCI systems IoRT, a testing environment has been created. The testing environment is suitable for performing supervisory or control functions of IoRT, based on attention level defined by processing EEG headset data. The structure of the system is shown on Fig.15

(Fig.16) shows the structure of the designed BCI based system, whereas the BCI application runs on the computer. The computer and the MindWave EEG headset connect to each other via Bluetooth technology, while the network device supporting remote control, applies wire transfer. Remote devices, the mobile robot controlled during the test, and the IP camera monitoring it, communicate with the network device via wireless TCP/IP connection.

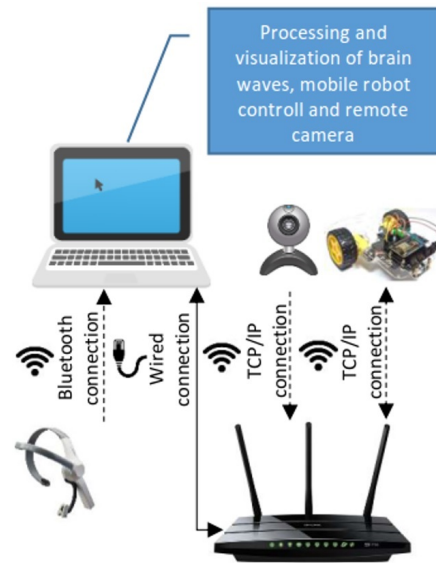


Fig. 15 Structure of BCI-based system

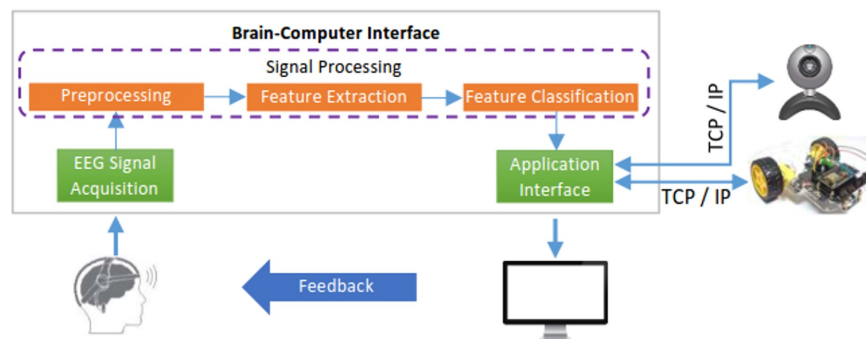


Fig. 16 Components of BCI-based system

5.3 Examine the response latency of BCI based IoRT control

By applying the testing environment, and the co-operation of testing subjects, it has been examined, with what latency were testing subjects able to give a command depending on attention level. The task of testing subject, was to increase their attention level above 60% when the light in the bottom-right corner of the BCI application turned red, and in case of exceeding that level, the mobile robot received via TCP/IP connection a speed level other than zero, making the robot move. The mobile robot provided a feedback of launching the robot, to the BCI application. During the test, the period between the light turning red, to the exceeding of 60% attention level, as well as the mobile robots feedback have been logged. This time period provides the latency of communication between the BCI system and the mobile robot. According to these, two tests have been performed, in the first case the BCI system and the IoRT device were in the same sub-network, and testing subjects could directly see the robot. In the second case, the IoRT device was in another sub-network, and testing subjects could see the robot only via a web camera, so remote control was performed. In both cases, the robot had to be launched three times in a row, increasing their attention level following the light turning red. In the test, 10 secondary school students, at ages varying between 15 and 17 participated, particularly 8 boys and 2 girls. Results of the two tests are shown in Table.1 and Table.2.

Table 1 TIME-VARYING CONTROL LATENCY TEST1

Test subjects	Speed reference latency [ms]	Network latency [ms]	Total latency [ms]
1.	5812.416±1723.323 ^a	0.971±0.038 ^a	5813.387±1723.361 ^a
2.	10722.329±2652.145 ^a	1.024±0.044 ^a	10723.353±2652.189 ^a
3.	9756.194±2152.876 ^a	0.992±0.042 ^a	9757.186±2152.918 ^a
4.	6917.111±2017.562 ^a	0.897±0.035 ^a	6918.008±2017.597 ^a
5.	7012.854±1352.984 ^a	0.945±0.039 ^a	7013.799±1353.023 ^a
6.	11121.955±2822.419 ^a	0.912±0.037 ^a	11122.867±2822.456 ^a
7.	4872.767±1248.728 ^a	0.948±0.038 ^a	4873.715±1248.766 ^a
8.	7786.844±1992.887 ^a	0.977±0.042 ^a	7787.821±1992.929 ^a
9.	12123.555±3465.385 ^a	0.956±0.043 ^a	12124.511±3465.428 ^a
10.	6992.721±2053.556 ^a	0.911±0.039 ^a	6993.632±2053.595 ^a
Average	8311.875±2450.515 ^a	0.953±0.040 ^a	8312.828±2450.525 ^a

^a SD: Standard Deviation

It is shown in the results of the first test, that the average time from the appearance of the signal to the launch of the robot, is almost 8 seconds, whose bigger part was of course spent for reaching higher attention level, while robot communication required only some milliseconds, depending on network latency. In case of the second test, performance of remote control were similar to the first test, in this case, average latency was also almost 8 seconds, and of course conscious influence of attention level required some seconds. As a conclusion, however, we can declare,

Table 2 TIME-VARYING CONTROL LATENCY TEST2

Test subjects	Speed reference latency [ms]	Network latency [ms]	Total latency [ms]
1.	7913.258±2013.187 ^a	2.832±0.153 ^a	7916.090±2013.340 ^a
2.	8124.935±2482.637 ^a	3.011±0.169 ^a	8127.946±2482.806 ^a
3.	7372.577±1923.812 ^a	2.723±0.159 ^a	7375.300±1923.971 ^a
4.	6123.544±1876.656 ^a	3.245±0.167 ^a	6126.789±1876.823 ^a
5.	9456.219±2913.173 ^a	2.792±0.156 ^a	9459.011±2913.329 ^a
6.	10011.684±3178.432 ^a	2.821±0.151 ^a	10014.505±3178.583 ^a
7.	5456.388±1642.681 ^a	2.984±0.158 ^a	5459.372±1642.839 ^a
8.	6234.387±1988.157 ^a	3.075±0.161 ^a	6237.462±1988.318 ^a
9.	11045.699±3411.424 ^a	3.066±0.158 ^a	11048.765±3411.582 ^a
10.	5923.333±1781.137 ^a	2.922±0.157 ^a	5926.255±1781.294 ^a
Average	7766.202±1907.147 ^a	2.947±0.159 ^a	7769.118±1907.101 ^a

^a SD: Standard Deviation

that conscious influence of attention level requires some seconds. During the performance of the tests, it was experienced, that testing subjects had to practice the use of devices for 10-20 minutes, before they became able to consciously influence their attention levels in that extent, which could be detected by the device.

6 Conclusion

In the article, the BCI system designed for human-computer based control of Internet of Robotic Things (IoRT) unit has been introduced, which supports modern robots with the opportunities of technology based on Internet of Things (IoT). Thanks to the performed BCI system and an IoRT device, such testing environment has been assembled, which is capable of achieving local or remote control of robots. In the testing environment, performance of human intervention and its latency thanks to the BCI system have been examined. According to the experiences of the performed tests, we can say, that for proper operation of BCI system, testing subjects had to practice the use of the device first, in order to reach appropriate results. On the other hand, testing subjects were able to perform human intervention only with some seconds latency, although this latency did not depend on whether testing subjects controlled the robot directly or by remote control. The BCI system give proper basics to test the technology, based on experiences got this way, and the definition of the ways of further improvements.

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