IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received February 21, 2020, accepted April 1, 2020, date of publication April 8, 2020, date of current version April 23, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2986511

Equivalent Data Information of Sensory and Motor Signals in the Human Body

TAEHYOUNG KIM AND SUNGKWON PARK, (Senior Member, IEEE)
Electronics and Computer Engineering Department, Hanyang University, Seoul 04763, South Korea

Corresponding author: Sungkwon Park (sp2996@hanyang.ac.kr)

This work was supported by the National Research Foundation of Korea (NRF) Grant Funded by the Korea Government, Ministry of Education (MOE), under Grant 2018R1D1A1A02048970.

ABSTRACT In this paper, the amount of information collected by sensory and motor organs is analyzed. Humans use their senses to recognize the information around them and to perform appropriate actions. To perform these processes, information is exchanged between organs via analog electrical signals. Analog electrical signals convey information transmitted from human sensory organs to the cerebrum or commands sent from the cerebrum to the appropriate motor organs. This paper analyzes the amount of analog signal information generated inside the human body and converts this information into equivalent digital data. This process is carried out in an effort to build a human-like humanoid based on the equivalent digital data. The analog information generated in the human body is investigated based on the medical publications to date. These analyses result in the bit rate and delay requirements of nervous systems that are built with digital networks. It is shown in this paper that both artificial eyes equivalently generate approximately 14 Gigabits from a one-time look when a humanoid performs at a human-like level. In addition, it is realized that the human body is more sensitive to pressure than to temperature since the pressure sensation generates, on average, more information than the temperature sensation.

INDEX TERMS Humanoid, in-robot network, sense, perception, motor, bit rates, requirement, delay.

I. INTRODUCTION

The human body is made up of numerous elements such as bones, muscles, nerves, organs, and so forth. Much information exchange must occur between these elements to maintain human homeostasis. This exchange of information is communicated through the peripheral nervous systems to the central nervous system, where the central nervous system issues appropriate action commands. At this time, each information is transmitted through a number of neurons. In general, there are approximately 86 billion neurons in the human body [1]. Many of these neurons are classified as sensory neurons, interneurons, and motor neurons according to their functions [2]. Sensory neurons make up the sensory nerves, and deliver the stimuli received by the sensory organs to the associated neurons. Interneurons make up the brain and spinal cord collectively judge the information received through sensory neurons and give appropriate instructions. Finally, motor neurons receive commands from the associated neurons and pass them on to the organs (arms, legs, etc.). Therefore, when a stimulus is delivered to the human body, it is processed in the order of sensory neurons, interneurons, and motor neurons, as above. Therefore, humans can maintain homeostasis because they perform appropriate body reactions and reflexes by recognizing the surrounding environment information collected from their sensory neurons. For example, if a human sees a ball through his or her eye, the sensory neurons in the eye transmit the stimulus to the interneurons. Stimulated interneurons transmit appropriate commands to one of the motor nerves in the legs. The motor nerves that receive the commands, tell those organs to exercise to move the muscles.

However, after recognizing external sensations, much time is required to activate the muscles if corresponding organ receives commands from the cerebrum. Thus, when a human is in a dangerous or urgent situation where homeostasis cannot be maintained, a reflex is issued from the spinal cord. In this case, the human body unconsciously enacts the reflexes. Reflexes are unconscious actions that occur reflexively when a person is irritated, regardless of the person's will. Therefore, when you touch a hot object, only the feeling of 'hot' is transmitted to the cerebrum; the action is initiated in the spinal cord, not the cerebrum [3]. When humans need

The associate editor coordinating the review of this manuscript and approving it for publication was Yassine Maleh.

to act fast and consciously, they decide upon their actions through different nervous systems.

A human has many neural networks, those comprising motor neurons and sensory neurons. These neural networks are comprised of many neurons. These neural networks are organically connected to organs and convey necessary information. For information to be communicated, the sensory organs must first recognize stimuli. These stimuli are recognized by the numerous receptors. These receptors must also recognize several stimuli simultaneously; thus, if one receptor is artificially implemented, it will consist of multiple sensors. This is because the quantification of the stimulus data received by the sensor is similar to the way the body perceives the surroundings through its receptors. Information transfer for perception is achieved through an organic neural network via electrical signals [4].

This paper analyzes the signals transmitted from the systems so that a human-like humanoid with digital communication networks can be built. In other words, this paper suggests an analogy of human neural networks with artificial communication networks in a humanoid by specifying the bit rates and other network parameters such as delays and data sizes. These efforts will be necessary if a humanoid is designed to mimic human functions. These communication network requirements will be important factors in designing communication networks for a human-like humanoid. These requirements will be used to select the proper communication network protocols, switches and bandwidths.

A human-like humanoid refers to a robot that has cognitive and motor functions as good as or better than those of humans. Regarding the previously developed humanoids, it is known that approximately 100 sensors and 70 actuators were required [5]. As the functionalities of humanoids become more sophisticated, the number of sensors is expected to increase. For example, humanoids need at least 80 motors or actuators in their faces alone to achieve the same sophisticated look as that of humans [6]. The number of sensors applied to humanoids in the future will further increase if they are designed to feel the temperature, touch sensations, and pain that can be felt at almost every point on human skin. Thus, it is essential to design a network that can properly connect a large number of sensors to meet the network requirements mentioned above. The network would be similar to a human nervous system. However, the research papers published so far have been conducted only for specific body parts such as hands and skin [7]. There has never been a research paper on the general nervous systems of the human body. In this paper, autonomic nervous systems such as those of the heart, stomach, and colon are not discussed because they are not directly controlled by the cerebrum.

This paper is organized as follows. Section II describes basic neural networks by classifying human neural networks into sensory and motor organs. Section III analyzes and explains the amount of information received by human sensory organs. Section IV analyzes and explains the amount of information received by human exercise-related organs. Finally, Section V concludes the paper.

II. BACKGROUND

The human nervous system is divided into the central nervous system and the peripheral nervous system. The central nervous system is divided into the brain and spinal cord, and the peripheral nervous system is divided into the somatic nervous system and the autonomic nervous system. The central nervous system primarily controls human behavior or the organs. The brain is divided into five parts: the cerebrum, cerebellum, interbrain, middle brain, and medulla [8]. Different parts of the brain control different kinds of behaviors. The spinal cord is responsible for the connections between peripheral nerves distributed in the sensory organs and muscles of the brain, as well as the backbone of unconditional reflexes. The peripheral nervous system consists mainly of nerve fiber masses and connects all body parts to the central nervous system. Clumps of nerve fibers are called 'nerves' and are classified as sensory or motor fibers by function [9]. This section introduces a human nervous system network, where signals from peripheral nerve receptors are passed to the brain to command various actions. In particular, Section A introduces the sensory organs of the peripheral nervous system, and Section B introduces the motor organs of the peripheral nervous system.

A. HUMAN SENSORY INFORMATION

This Section introduces the sensory organs of the peripheral nervous system. The peripheral nervous system transmits stimuli received by sensory organs in each part of the body to the brain and spinal cord. Also, the peripheral nervous system is the nervous system that delivers integrated and coordinated responses in the brain and spinal cord to the skeletal muscles, visceral muscles, and various glands of the body. It is divided into the autonomic nervous system and the somatic nervous system, which is again divided into sympathetic nerves and parasympathetic nerves. The autonomic nervous system consists of sympathetic and parasympathetic nerves. The somatic nervous system consists of 12 pairs of cranial nerves and 31 pairs of spinal nerves, which primarily correspond to the exercise and skin sensory organs. The autonomic nervous system is distributed in the intestines, blood vessels, etc. and controls the functions of each organ unconsciously or reflexively [9]. As such, a human nervous system has a very complex configuration. This Section explains the basic theory behind the analysis of the amount of information from the five human senses, skin and muscle movements.

The average surface area of an adult's total skin is approximately 2 m^2, which means that our skin is one of the largest body organs [10]. The skin not only protects the muscles, internal organs, blood vessels and nerves from the outside environment but also detects and transmits millions of signals from the outside environment to the brain. In other words, human skin maintains body temperature through collected information and plays an important role in informing the body of surficial danger from external hazards. The skin has five internal sensory points that are used to feel irritations. The sensory points of the skin are composed of touch, pressure, hot, cold, and pain points. In addition, the skin sensory points are distributed throughout the body, with the number varying depending on the part of the body. In general, human skin has 0 to 3 hot points, 6 to 23 cold points, and 100 to 200 pressure points per square centimeter [11]. In addition, when a stimulus is delivered to a sensory point, the stimulus is transmitted to the brain for recognition. At this time, the transmission speed of the senses transmitted from the sensory point to the brain depends on the thickness of the corresponding nerve fibers. The thickness of the nerve transmitting the signal received at the tactile and pressure points is approximately $5 \sim 12$ μm. Its transmission speed is approximately $30 \sim 70$ m/s. In addition, the pain points and temperature sensory points are divided in two according to their diameters. A relatively large diameter is approximately $2 \sim 5$ μm. In this case, the transfer speed is approximately $12 \sim 30$ m/s. The temperature sensory points have relatively large diameters. On the other hand, the relatively small diameters range from 0.4 to 1.2 μm. Their transfer speeds are in the range of approximately 0.5 to 2 m/s [9]. The pain points have relatively small diameters [12].

In the remaining part of this section, the other four senses, i.e., smell, sight, hearing, and balance, are briefly introduced.

First, human sight is the sense perceived through the eye. Through this sensation, a human can recognize the sizes and shapes of objects, light, and perspective. If a still image that can be observed by human eyes is converted into pixels, it can be expressed as approximately 576 million pixels [13]. Moreover, because 70% of all sensory receptors in the human body are in the eyes, vision is the most important sense for a human [14].

The sense of smell occurs owing to chemicals in the air. In other words, the receptors in the nose sense chemicals to recognize the environment. There are approximately 1,000 receptors that can detect chemicals in the nose, and the number of chemicals that each receptor detects is known to be 17 [15].

Hearing refers to the sense of sound. In the process of hearing, the frequencies and intensities of sound waves transmitted to the ears through media such as air or water are mechanically sensed. In general, audible frequencies of 20 to 20,000 Hz can be heard by humans, and very sensitive people can hear up to 30,000 Hz. As people grow older, the range of these frequencies decreases [16]. In addition, the ears have semicircular canals that are responsible for the sense of equilibrium of the human body. These semicircular canals consist of three rings, each 90 degrees apart from the others. Lymphatic fluid fills in these semicircular canals to detect movements in each direction [17].

B. HUMAN MOTOR INFORMATION

In general, a human is controlled by the cerebrum to perform muscle movements. However, there is an unconscious response to a stimulus regardless of the control of the cerebrum. This reaction depends on conscious and unconscious reactions such as reflections. The cerebrum processes the stimuli of conscious responses received from the sensory nerves, and the cerebrum sends commands to the motor nerves. The commands received from the cerebrum cause the motor nerves to transmit to the motor organs to perform proper movements. Unconscious reactions (reflections) are unconscious responses to stimuli, regardless of the commands of the cerebrum. Since an unconscious reaction is not controlled by the brain, the reaction occurs through the reflex center, i.e., the spinal cord, the medulla, and the middle brain. Therefore, the response rate is faster than that of a conscious response; hence, the human body can quickly react to protect itself from various dangers. Representative examples of unconscious reactions include knee reflections, sweating, coughing, and pupillary reflexes.

A human has approximately 640 skeletal muscles. The number of skeletal muscles is greatest in the face, with approximately 80 muscles, and least in the hands each with approximately 10 muscles [18]. These muscles are moved by the commands received from the motor nerves. Each motor nerve carries a command from the central nervous system and delivers it to the muscles. The muscles with the command perform the appropriate responses.

III. EQUIVALENT DIGITAL INFORMATION FROM THE HUMAN SENSORY SYSTEM

Until now, the systems of sensory and motor neurons in humans have been analyzed. As mentioned in the Introduction, this Section begins to quantify the amounts and flows of information collected from receptors in the peripheral nervous systems in terms of data bits and bandwidths. To obtain the data bits and bandwidths, the bands of the senses in which the body's receptors respond most sensitively are quantified.

A. SKIN

A human has different skin sensory receptors for recognizing different senses. Based on the information perceived by a skin sensory container, a human can recognize the environment their body is in.

To obtain the equivalent digital human information generated from the sensory system, the senses of warmth and coldness must be integrated into one temperature sense. This is because the information generated by two groups of sensory points can be scaled to a single temperature value ranging from coldness to hotness. A pressure sensory point can represent touch, pressure, and pain because these can also be expressed as a single value depending on the range. For example, a slight touch can be expressed as a small number represented by the touch weight, and the pain caused by the pressure of a heavy object can be expressed as its weight.

A human has different ranges of temperatures and pressures that can be felt in different parts of the body. The reason is that sensory points are distributed in a human body differently. Therefore, the number of sensory points per body part is calculated using the sensory points distributed per unit area multiplied by the total skin unit area. The total skin area is assumed to be the average skin area of an adult male (2.4 m^2), and the body parts are largely classified as follows: arms and hands, legs and feet, the head, and the trunk [19]. The skin ratio of a human body and the obtained skin area are shown in Table 1. In addition, the number of temperature sensory points of each skin per unit area mentioned in Section 2 is shown in Table 2.

TABLE 1. **Human skin area.**

Body part	Skin area ratio (%)	Skin area (cm^2)
Arms	20	4,800
Hands	5	1,200
Legs	34.4	8,300
Feet	6.2	1,500
Forehead	0.06	14
Nose	0.03	7.2
Lip	0.01	2.4
Cheek	7.4	1,776
Chest and abdomen	9.2	2,200
Back	8.6	2,100

TABLE 2. **Number of temperature sensory points per unit area.**

Body part	Number of temperature points per cm^2 (num)
Arm	8
Palm	10
Back of the hand	6
Leg	6
Top of the foot	5.6
Sole	3.4
Forehead	8
Nose	9
Lip	19
Cheek	9
Chest and abdomen	12
Back	8

The number of sensory points for each part is derived from the ratio of hot and cold points per body area and unit area. On the basis of the number of temperature points per unit area, the number of temperature points, data size and bit rate of each body part are calculated.

The number of temperature sensory points for each body part is calculated by multiplying the number of temperature sensory points per unit area by the area of each body part. In the case of the hand, foot, and torso, the distribution of temperature sensory points on the upper and lower surfaces is different. Therefore, when calculating the temperature sensory points of the hand, foot, and torso, the number of temperature sensory points is calculated by applying different numbers of temperature sensory points on the top and bottom surfaces. In addition, the temperature change felt by a person is analyzed to obtain the data size received from the receiver. The temperatures that a human can feel most sensitively range from 5 °C ∼ 45 °C, and a human can feel temperature differences with a resolution of 0.02 °C. Therefore, 1 °C can be divided into 50 intervals of 0.02 °C increment, with a total of 2,000 temperature changes that can be felt because of detection occurring over a total range of 40 °C [20], [21]. These 2,000 temperature changes can be represented as 11 bits, and the total data size can be obtained by multiplying 11 bits by the number of temperature sensory points. To determine the equivalent bit rate of a signal generated from a receptor, the number of collections per second at a receptor is investigated. The temperature sensory points collect the ambient temperature information approximately 50 times a second [22]. Therefore, the bit rate can be obtained by multiplying the data size by the frequency.

Finally, the speed and distance of signal transmission are analyzed to find the delay time in transferring the temperature information collected from the temperature sensory point to the head. The speed at which temperature data collected from the temperature sensory point are transferred is approximately 30 m/s [12]. The length is also set to the distance from the brain to the furthest receptor. This is because a strict delay time can be set and the minimum delay time can be set. For example, in the case of the hands, the length is set from the head to the tip of the finger, and in the case of the legs and feet, the length is set from the head to the tip of the toe. Therefore, the delay time is obtained by dividing the length by the transmission speed. Tables 3 to 5 show the final information collected from the temperature sensory points for each body part.

Next, the amount of information collected at the pressure points is analyzed. The pressure that humans feel is different in intensity at each body part, similar to the temperature felt at the sensory points. The reason is that the number of pressure sensory points is different for each part of the human body. Although the exact number of pressure sensory points in each part of the human body is currently unknown, the minimum distance is experimentally known, as shown in Table 6; the minimum distance refers to the smallest distance between two points at which the skin can still be separately felt [23].

The number of pressure sensory points per unit area is derived using the information in Table 6. The number of pressure sensory points is calculated by multiplying the total

TABLE 3. Information regarding the data collected from the temperature sensory points.

Body part	Number of temperature spots (num)	Length(m)
Arms	38,400	1
Hands	9,600	1.5
Legs	49,536	1.8
Feet	11,904	2
Forehead	11,904	0.2
Nose	65	0.2
Lip	46	0.2
Cheek	15,984	0.2
Chest and abdomen	26,496	0.9
Back	12,512	0.9

TABLE 4. Transmission speed and delay time of data from temperature sensory points.

Body part	Transmission speed (m/s)	Delay time(sec)
Arms	30	0.033
Hands	30	0.038
Legs	30	0.06
Feet	30	0.067
Forehead	30	0.006
Nose	30	0.006
Lip	30	0.006
Cheek	30	0.006
Chest and abdomen	30	0.03
Back	30	0.012

TABLE 5. Data sizes and bit rates of data from temperature sensory points.

Body part	Data size (bit)	Bit rate(bps)
Arms	528,000	26,400,000
Hands		
Legs	675,840	33,792,000
Feet		
Forehead	178,306	8,915,280
Nose		
Lip		
Cheek		
Chest and abdomen	473,088	23,654,400
Back		

TABLE 6. Minimum distance felt at which two separate points can still be felt independently.

Body part	Minimum distance (mm)
Fingers	2-3
Upper Lip	5
Cheek	6
Nose	7
Palm	10
Forehead	15
Foot	20
Belly	30
Forearm	35
Upper arm	39
Back	39
Shoulder	41
Thigh	41
Calf	45

area in Table 1 with the number of pressure points present per unit area (cm^2). Through this derivation, this paper derives the number of pressure sensory points for each part of the human body. By doing so, the number of pressure sensory points on each body part is determined, as shown in Table 7.

TABLE 7. Number of pressure sensory points.

Body part	Number of the pressure sensory points per unit area (num)	Number of pressure sensory points (num)
Arm	13	63,828
Palm	58	69,600
Finger tip	241	7,698
Leg	13	109,784
Foot	28	42,393
Forehead	38	551
Nose	84	603
Lip	118	284
Cheek	98	174,233
Chest and abdomen	19	41,480
Back	14	71,097

Next, pressure sensations received at the pressure sensory points are analyzed to present them with the binary data. To do this, the range of pressure that a human can feel is quantified, and this value must be expressed in binary with the appropriate number of bits. Let N_p be the entire pressure range that human can sense and N_r be the value obtained by dividing the entire pressure range by the minimum difference, D_m, in pressure that humans can feel. In this case, let K_b be the minimum number of bits needed to represent N_r as a binary number. This K_b is the minimum binary data size for indicating pressure.

$$\mathbf{K_b} = \ulcorner \mathbf{\log_2 N_r} \urcorner. \tag{1}$$

$$\mathbf{N_r = N_p / D_m}. \tag{2}$$

Here in equation 1, $\lceil x \rceil$ indicates the smallest integer greater than or equal to x. For example, assuming that the pressure range is 100 and the minimum pressure difference a human can feel is 4, a total of 100 divided by 4 would be 25; hence, a binary to express this minimum would require 5 bits. Therefore, K_b, which digitally expresses the pressure sensory range N_r, will be 5 bits. The maximum pressure at one pressure sensory point for an adult is 1.98 N [24]. If the pressure exceeds 1.98 N, a human does not feel a difference between their senses and thus feels the same pain. To convert this pressure to weight, one can divide it by the acceleration due to gravity, that is, 9.8 N/kg, resulting in 0.202 kg, which is the weight at which pressure can be felt at one pressure sensory point. Let g be the acceleration by gravity and F_p be the maximum pressure force that human can feel. Let W is the weight that feel the pressure force at one pressure sensory point. The relation between these parameters is expressed in equation 3.

$$\mathbf{W = F_p / g}. \tag{3}$$

Nevertheless, the reason why a human can feel more than 10 kg is as follows. A human uses muscles to lift objects and feels pressure only through multiple pressure sensory points on the part of the skin that touches them. For example, if a human lifts an object by hand, the human feels pressure at the pressure sensory point of the hand touching the object, and the weight is felt through the muscles of the arm and shoulder.

The minimum change in weight at which a human feels pressure is 0.000158 kg [7]. To find the number of weight changes humans can feel, 0.202 kg is divided by 0.000158 kg. From this calculation, the number of pressures changes that a human can feel is 1,278. The above value can be expressed as 11 bits, and the data size can be obtained by multiplying this value by the number of pressure sensory points. The 11 bits are very sophisticated values and quantize the data collected at the pressure sensory point linearly during sampling.

The pressure reception period per second is analyzed to obtain the bit rate value received at the pressure sensory point. On average, the frequency of vibration felt by human skin is up to 250 Hz. Thus, if a human is subjected to vibration with a period above 250 Hz, the pressure sensory points receive some stimulus, not a vibration. Therefore, the frequency at which pressure is felt can be set to 250 Hz.

Finally, the delay time for transmitting information collected from pressure sensory points to the brain is derived. The speed at which information gathered from pressure sensory points is transmitted to the brain is approximately 70 m/s [12]. In addition, the distance is the length from the sensory points to the brain. On the basis of these facts, the delay time of transmission from the pressure sensory points to the brain can be obtained. The information regarding the final pressure sensory point derived by considering all the above items is shown in Tables 8 to 10.

TABLE 8. Information regarding data from pressure sensory points.

Body part	Number of pressure sensory points (num)	Length (m)
Arm	63,828	1
Palm	69,600	1.5
Finger tip	7,698	1.8
Leg	109,784	2
Foot	42,393	2
Forehead	551	0.2
Nose	603	0.2
Lip	284	0.2
Cheek	174,233	0.9
Chest and abdomen	41,480	0.9
Back	71,097	0.9

TABLE 9. Transmission speed and delay time of data from pressure sensory points.

Body part	Transmission speed (m/s)	Delay time (sec)
Arm	70	0.014
Palm	70	0.021
Finger tip	70	0.026
Leg	70	0.029
Foot	70	0.029
Forehead	70	0.003
Nose	70	0.003
Lip	70	0.003
Cheek	70	0.013
Chest and abdomen	70	0.013
Back	70	0.013

B. VISION

The amount of information collected from human eyes is analyzed in this part. The total number of pixels per frame and that of frames collected per second are analyzed. In addition, the number of colors that the human eyes can recognize is analyzed. As mentioned in the background, human eyes do not recognize many pixels at a time but can look around and see all that is desired. If this is calculated in pixels, it can be converted into a result of approximately 576 million pixels [13]. The equation explaining this relationship is given as shown below. For the resolution of the human eye, let's try a "small" example. Consider a view in front of you that is 90 degrees by 90 degrees, like looking through an open window at a scene. The number of pixels would be

TABLE 10. Data sizes and bit rates of data from pressure sensory points.

Body part	Data size (bit)	Bit rate (bps)
Arm	702,108	175,527,000
Palm	765,600	191,400,000
Finger tip	84,678	21,169,500
Leg	1,207,624	301,906,000
Foot	466,323	116,580,750
Forehead	6,061	1,515,250
Nose	6,633	1,658,250
Lip	3,124	781,000
Cheek	1,916,563	479,140,750
Chest and abdomen	456,280	114,070,000
Back	782,067	195,516,750

according to [13]

$$90 \text{ degrees} \times 60 \text{ arc-minutes/degree} \times 1/0.3 \times 90 \times 60 \times 1/0.3 = 324,000,000 \text{ pixels (324 million pixels)}. \quad (4)$$

At any one moment, the human eyes actually do not perceive that many pixels, but moves around the scene to see all the detail. But the human eye really sees a larger field of view, close to 180 degrees. Let's be conservative and use 120 degrees for the field of view. Then human would see

$$120 \times 120 \times 60 \times 60/(0.3 \times 0.3) = 576 \text{ million pixels}. \quad (5)$$

However, the full angle of human vision would require even more million pixels.

The human eyes can recognize approximately 1 million colors [25]. The reason why the human eyes can recognize colors is because cone cells in the eye recognize colors. There are three groups of cone cells which recognize red, green, and blue, respectively. Cone cells also transmit the information regarding colors recognized to the brain [26]. To express the analog color signal recognized by the eyes as digital binary bits, each bit of red, green, and blue can be represented by 8 bits since 24 bits may express more than 1 million colors. Thus, when the color recognized by the human eyes is expressed in binary bits, it can be expressed as a total of 48 bits for the two eyes.

Similar to a camera, a human eye recognizes its surroundings by recognizing consecutive frames. The data size collected from an eye for a single look can be obtained by multiplying the total number of pixels by the number of bits required to express a color for a pixel. This corresponds to the total number of bits per frame from a single look. In general, the human eyes recognize frames at a rate of approximately 20 fps [27]. The bit rate of transmission from an eye to the brain can be calculated by multiplying the total number of bits by the frame rate. Table 11 shows the total number of bits per frame and the bit rate to express the bio-signal generated from two eyes.

TABLE 11. Data sizes and bit rates of data from vision sense.

Unit	Data size per sample (bit)	Frequency per second (Hz)	Bit rate (bps)
Vision	27 Giga	20	553 Giga

C. HEARING, SMELLING, AND VESTIBULAR

This section analyzes the amount of information in bits generated from hearing, smelling, and the vestibular sense. The human auditory sense listens to the surrounding sounds through the ears. In general, the maximum audio frequency a human can hear is 22,000 Hz. In converting these frequencies to digital data, the sampling frequency should be 44.1 kHz. In this case, the quantization depth uses 16 bits. The reason is that the quantization depth at which humans do not notice the difference in a sampled sound is 16 bits and the sampling frequency is 44.1 kHz [28]. Thus, the number of bits collected from both ears per sample would be 32 bits. The bit rate can be obtained by multiplying this value by the sampling frequency.

A human ear not only hears sounds but also plays an important role in human balance. As mentioned in the background, there are semicircular canals in the ears. These semicircular canals sense human tilt, rotation, and gravity. This part of the paper analyzes the reasonable number of bits necessary to express the human balance information.

When the body changes position or begins a movement, the weight of the membrane bends the stereocilia and stimulates the hair cells. Hair cells send signals down sensory nerve fibers, which are interpreted by the brain as motion. When the head is in a normal upright position, the otolith presses on the sensory hair cell receptors. This pushes the hair cell processes down and prevents them from moving side to side. However, when the head is tilted, the pull of gravity on the otoliths shift the hair cell processes to the side, distorting them and sending a message to the central nervous system that the head is no longer level but now tilted [29]. As stated above, the human balance mechanism is complicated to analyze. Nonetheless, three different signals for tilt, rotation, and gravity are sent from the ears to the brain. To represent these three signals in bits, we refer to the gyro and acceleration sensor, GY-521 MPU-6050 from TDK, used in other humanoids [30]. This sensor is typically used in many robots and automobiles [31]. The binary expressions of the x-, y-, and z-axes of the gyro sensor, which detects the tilt and rotation, are set to 16 bits, and that of the acceleration sensor is also set to 16 bits. Therefore, the data generated from one ear is represented by 48 bits, and 96 bits are obtained by combining the data from both ears. In addition, since the sense of balance is very important for humans, the balance data is collected 1,000 times per second by referring to the amount of data collected by the sensor. It is assumed that the sampling rate for balance is 1,000 Hz for humans. The total number of data bits is obtained by multiplying 96 bits with 1,000 Hz to yield 96,000 bits per second.

Finally, a human's sense of smell recognizes the surrounding environment by detecting chemical substances in the air via receptors in the nose. In addition, the nose filters out some of the harmful chemicals and substances that enter the respiratory organ. Therefore, in this part, the amount of information collected from the nose is analyzed. There are approximately 1,000 receptors in the nose, and the number of senses detected by each receptor is known to be 17 [32]. Therefore, the number of senses detected can be represented by 5 bits.

The sense of smell occurs when humans inhale. The amount of information received for the sense of smell may vary depending on the breathing frequency. In this paper, we analyze the case where the breathing frequency is relatively faster. This is because it is necessary to analyze the case where the amount of smell information is relatively large. During exercise, the breathing frequency is approximately 50 breaths per minute. Therefore, the frequency is approximately 0.83 Hz. On this basis, the data size and bit rate of the smell sense can be obtained. The data size is obtained by multiplying 1,000 receivers by 5 bits. The bit rate can be obtained by multiplying the data size by 0.83 Hz, which is the breathing frequency during exercise. Therefore, the bit rate of the smell sense is estimated to be less than 4,150 bps. Table 12 shows the data sizes and bit rates of the data for hearing, smelling and balancing.

TABLE 12. Data sizes and bit rates of data from special senses.

Special sense	Data size (bit)	Frequency (Hz)	Bit rate (bps)
Hearing	32	44,100	1.4M
Balancing	96	1,000	96K
Smelling	5,000	0.83	4,150

IV. EQUIVALENT DIGITAL INFORMATION TO BIOLOGICAL SIGNALS FROM HUMAN MOTOR SYSTEM

The amount of digital information of the biological signals sent to the muscles in the human body is analyzed in this Section. As mentioned in the background, the human body moves under the control of the cerebrum or due to the reflexes of the spinal cord. If these movements are not carried out properly, they can lead to human injuries and accidents, which can be life threatening. In addition, sophisticated movements of the human body are necessary to appropriately respond to danger. This Section includes separate analyses of the individual parts of the human body, such as the face, lips, neck, waist, arms, hands, legs, and feet. To do this, the number of muscles in each part is investigated [33]. These analyses include the delay time as well as the data size and bit rate of the equivalent binary digital data of the biological signals received from the brain.

TABLE 13. Information regarding the transmission of data to the human muscles.

Body part	Number of muscles (num)	Length (m)
Face	80	0.2
Neck	10	0.3
Lips	6	0.15
Waist	55	0.9
Arms	24	1
Hands	10	1.15
Legs	37	1.72
Feet	12	2

TABLE 14. Transmission speed and delay time of data sent to the human muscles.

Body part	Transmission speed (m/s)	Delay time (sec)
Face	120	0.0016
Neck	120	0.0025
Lips	120	0.00125
Waist	120	0.0075
Arms	120	0.0083
Hands	120	0.0095
Legs	120	0.0143
Feet	120	0.0166

TABLE 15. Data sizes and bit rates of data sent to the human muscles.

Body part	Data size (bit)	Bit rate (bps)
Face	560	33,600
Neck	70	4,200
Lips	42	2,520
Waist	385	23,100
Arms	168	10,080
Hands	70	4,200
Legs	259	15,540
Feet	84	5,040

Human muscles move through relaxation and contraction. The muscle size during contraction is approximately 1.5 times longer than that during relaxation. This muscles change can be represented with approximately 100 differences [29]. This change therefore can be represented by 7 bits. The total number of bits for the biological signals of all muscles can be obtained by multiplying the number of total muscles by 7. In addition, the brain transmits a command signal to each muscle 60 times per second; thus, so the frequency is set to 60 Hz [34]. The bit rate for a muscle is obtained by multiplying the frequency and the data size.

Finally, the muscle neurotransmission speed is approximately 120 m/s, which is much faster than the sensory neurotransmission speeds [12]. Therefore, the delay times are obtained by dividing the distances from the brain to the muscles by the neurotransmission speed from the brain to the muscles. Table 13 shows the number of muscles of different parts. Tables 14 to 15 show the amount of information derived from a human motor system.

V. CONCLUSION

In this paper, the amount of information collected by a human's sensory organs and the commands transmitted from the cerebrum to the motor organs are analyzed to convert biological signals in the human body to digital information such as binary bits and the bit rate. Various neurobiological studies of our human bodies are referred to in these analyses. Analog bio-neurological signals are converted to digital values based on reasonable assumptions for the corresponding resolutions and frequencies that humans can distinguish and feel. These analyses can be valuable when human-like humanoids and artificial limbs are implemented in digital bio-mechanical systems in the future. For example, artificial units that will be used to mimic human organs including muscles have to be interconnected with a central processing unit (CPU) for brains with in-robot networks (IRNs). IRN requires many heterogeneous networks in different parts with appropriate bandwidths, maximum delay limits, and various qualities of services (QoSs). The values of digital information data that emerged from this paper may answer these requirements.

According to our research, human feet have the most temperature sensory points, namely, approximately 49,000. If this is converted to binary bits with the equivalent information, it turns out to be approximately 675 Kbits. In addition, the bit rate of transmission to the brain from both feet is approximately 33 Mbps. The skin part with the most concentrated temperature sensory points per unit area is found to be the human lips. The number of temperature sensory points of the lips is 19 per cm^2. Therefore, our lips are the most temperature-sensitive parts of our body. The nerve fiber used to deliver temperature information has a transmission speed of approximately 30 m/s, which is derived based on the distance from each organ to the brain. The organ with the shortest delay time is the face, which is analyzed to have a delay of approximately 6 milliseconds.

The most pressure-sensitive body part is the cheek. There are approximately 174,000 pressure sensory points on both cheeks, and the equivalent data bits collected from the pressure sensory points per unit time is approximately 1,916 Kbits. Since our brain collects pressure data about 250 times per second, the data rate is approximately 479 Mbps. The pressure information is found to be relatively greater than the temperature information. This is because the number of pressure sensory points is much greater than the number of temperature sensory points.

This paper analyzes the information regarding the visual, auditory, olfactory, and balance senses, which are regarded as four of the five typical human special senses, excluding taste. Taste is perceived by our tongue, similar to our skin, and is unlikely to be urgently implemented in humanoids in the near future. This paper does not analyze the taste sense. However, it is one of the special senses to be eventually implemented in the future. Among the four special senses, the data bits collected through the eye per look is 14 Gigabits, which is the largest among the sensory organs.

For the human muscles, the facial muscles are the ones that receive the commands with the greatest number of bits from the cerebrum. This is because the human face has more muscles than any other part of the body. The equivalent data bits are approximately 560 bits per second. Facial muscles can express a wide variety of expressions based on the biological signals received from the cerebrum. The delay time from the cerebrum to the facial muscles is 16 milliseconds, which is the shortest delay time for human muscles.

In future research, actual artificial digital networks will be designed to support humanoids in carrying out sensing and acting like humans. To do this, a domain configuration can be considered for an efficient data network. This may reduce the traffic in the backbone network connected to each domain [35], [36]. Moreover, different communication network protocols need to be considered to reduce costs, improve efficiencies, and guarantee satisfaction of the communication network requirements for bandwidths, delays, and collisions, especially under traffic congestion, and network survivability when partial failures occur [37], [38].

REFERENCES

[1] S. Herculano-Houzel, "Isotropic fractionator: A simple, rapid method for the quantification of total cell and neuron numbers in the brain," *J. Neurosci.*, vol. 25, no. 10, pp. 2518–2521, Mar. 2005.

[2] W. E. Armstrong, "Morphological and electrophysiological classification of hypothalamic supraoptic neurons," *Prog. Neurobiol.*, vol. 47, nos. 4–5, pp. 291–339, Nov. 1995.

[3] D. F. Cechetto and J. K. Shoemaker, "Functional neuroanatomy of autonomic regulation," *NeuroImage*, vol. 47, no. 3, pp. 795–803, Sep. 2009.

[4] O. G. Martinsen and S. Grimnes, *Bioimpedance and Bioelectricity Basics*. New York, NY, USA: Academic, 2011.

[5] H.-P. Huang, J.-L. Yan, T.-H. Huang, and M.-B. Huang, "IoT Based for Humanoid Robots," *J. Chin. Inst. Engineers*, vol. 40, no. 7, pp. 603–613, 2017.

[6] K. Won, P. D. Chung, *Gross Anatomy Board Review*. Hagerstown, MD, USA: Lippincott Williams, 2005, p. 364.

[7] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—From humans to humanoids," *IEEE Trans. Robot.*, vol. 26, no. 1, pp. 1–20, Feb. 2010.

[8] R. S. Frackowiak, *Human Brain Function*. Amsterdam, The Netherlands: Elsevier, 2004.

[9] J. K. Mai and G. Paxinos, *The Human Nervous System*. New York, NY, USA: Academic, 2011.

[10] K. Brooke-Wavell, P. R. M. Jones, and G. M. West, "Reliability and repeatability of 3-D body scanner (LASS) measurements compared to anthropometry," *Ann. Human Biol.*, vol. 21, no. 6, pp. 571–577, Jan. 1994.

[11] F. McGlone and D. Reilly, "The cutaneous sensory system," *Neurosci. Biobehavioral Rev.*, vol. 34, no. 2, pp. 148–159, Feb. 2010.

[12] P. H. Stern, "Neuroscience fundamentals for rehabilitation," *Amer. J. Phys. Med. Rehabil.*, vol. 78, no. 3, p. 254, May 1999.

[13] R. N. Clark. (2009) *Notes on the Resolution and Other Details of the Human Eye*. [Online]. Available: http://clarkvision.com/articles/eye-resolution.html

[14] C. A. Curcio, K. R. Sloan, R. E. Kalina, and A. E. Hendrickson, "Human photoreceptor topography," *J. Comparative Neurol.*, vol. 292, no. 4, pp. 497–523, Feb. 1990.

[15] S. H. Lee, O. S. Kwon, H. S. Song, S. J. Park, J. H. Sung, J. Jang, and T. H. Park, "Mimicking the human smell sensing mechanism with an artificial nose platform," *Biomaterials*, vol. 33, no. 6, pp. 1722–1729, Feb. 2012.

[16] B. Masterton, H. Heffner, and R. Ravizza, "The evolution of human hearing," *J. Acoust. Soc. Amer.*, vol. 45, no. 4, pp. 966–985, 1969.

[17] W. C. Van Buskirk, R. G. Watts, and Y. K. Liu, "The fluid mechanics of the semicircular canals," *J. Fluid Mech.*, vol. 78, no. 1, pp. 87–98, Nov. 1976.

[18] S. V. Brooks, "Current topics for teaching skeletal muscle physiology," *Adv. Physiol. Educ.*, vol. 27, nos. 1–4, pp. 171–182, 2003.

[19] A. Arens and H. Zhang, "The skin's role in human thermoregulation and comfort," in *Proc. Thermal Moisture Transp. Fibrous Mater.*, 2006, pp. 560–602.

[20] H. Merskey and N. Bogduk, Eds., "Part III: Pain terms, a current list with definitions and notes on usage," in *Classification of Chronic Pain* (IASP Task Force on Taxonomy), 2nd ed. Seattle, WA, USA: IASP Press, 1994, pp. 209–214.

[21] L. Jones, "Thermal touch," *Scholarpedia*, vol. 4, no. 5, p. 7955, 2009.

[22] B. G. Green, "Temperature perception and nociception," *J. Neurobiol.*, vol. 61, no. 1, pp. 13–29, Oct. 2004.

[23] R. Gonzalez. *T10 Limits to Human Perception and How They Shape Your World*. Accessed: Jul. 17, 2012. [Online]. Available: https://io9.gizmodo.com/10-limits-to-human-perception-and-how-they-shape-yo-5926643

[24] T. Xu, W. Wang, X. Bian, X. Wang, X. Wang, J. K. Luo, and S. Dong, "High resolution skin-like sensor capable of sensing and visualizing various sensations and three dimensional shape," *Sci. Rep.*, vol. 5, no. 1, Oct. 2015, Art. no. 12997.

[25] S. Ralston, D. K. Stevenson, and S. E. Campana, "Otolith microstructure examination and analysis," *Copeia*, vol. 1993, no. 4, p. 1197, Dec. 1993.

[26] C. W. Oyster, *A Human Eye*. Sunderland, MA, USA: Sinauer, 1999.

[27] J. Nathans, "The evolution and physiology of human color vision: insights from molecular genetic studies of visual pigments," *Neuron*, vol. 24, no. 2, pp. 299–312, 1999.

[28] M. H. U. Abdeen, U. S. Khan, and J. Iqbal, "A multipurpose vehicle tracking system based on ARM CORTEX-M3 STM32, HMC5883L, MPU-6050, GSM and GPS," *J. Traffic Logistics Eng.*, vol. 4, no. 1, pp. 7–12, Jun. 2016.

[29] H. S. Gasser and A. V. Hill, "The dynamics of muscular contraction," *Roy. Soc. London, B, Containing Biol.*, vol. 96, no. 678, pp. 398–437, 1924.

[30] (Aug. 2013). *MPU-6000 and MPU-6050 Product Specification Revision 3.4, PS-MPU-6000A-00*. [Online]. Available: https://store.invensense.com/datasheets/invensense/MPU-6050_DataSheet_V3%204.pdf

[31] B. Tag, J. Shimizu, C. Zhang, K. S. Kunze, N. Ohta, and K. Sugiura, "In the eye of the beholder: The impact of frame rate on human eye blink," in *Proc. 34th Annu. CHI Conf. Hum. Factors Comput. Syst.*, May 2016, pp. 2321–2327.

[32] B. Malnic, J. Hirono, T. Sato, and L. B. Buck, "Combinatorial receptor codes for odors," *Cell*, vol. 96, no. 5, pp. 713–723, Mar. 1999.

[33] S. Longenbaker, *Anatomy & Physiology: Mader's Understanding Human Anatomy & Physiology*. New York, NY, USA: McGraw-Hill, 2010.

[34] A. Pras and C. Guastavino, "Sampling rate discrimination: 44.1 kHz vs. 88.2 kHz," in *Audio Engineering Society Convention*. New York, NY, USA: Audio Engineering Societym, May 2010.

[35] J. Lee and S. Park, "Time-sensitive network (TSN) experiment in sensor-based integrated environment for autonomous driving," *Sensors*, vol. 19, no. 5, p. 1111, 2010.

[36] H. Lee, J. Lee, C. Park, and S. Park, "Time-aware preemption to enhance the performance of Audio/Video bridging (AVB) in IEEE 802.1 TSN," in *Proc. 1st IEEE Int. Conf. Comput. Commun. Internet (ICCCI)*, Wuhan, China, Oct. 2016, pp. 80–84.

[37] J. Lee and S. Park, "New asymmetric data transmission method for in-vehicle network," in *Proc. Int. Symp. Intell. Signal Process. Commun. Syst. (ISPACS)*, Taipei, Taiwan, Dec. 2019, pp. 1–2.

[38] V. Gavrilut, L. Zhao, M. L. Raagaard, and P. Pop, "AVB-aware routing and scheduling of time-triggered traffic for TSN," *IEEE Access*, vol. 6, pp. 75229–75243, 2018.

TAEHYOUNG KIM received the B.S. degree in electronics engineering from Dankook University, Cheonan, South Korea, in 2018, and the master's degree from Hanyang University, in February 2020, where he is currently pursuing the Ph.D. degree. His research interests include in-vehicle networks, in-robot networks, and the Internet of Things (IoT).

SUNGKWON PARK (Senior Member, IEEE) received the B.S. degree from Hanyang University, Seoul, South Korea, in 1982, the M.S. degree from the Stevens Institute of Technology, Hoboken, NJ, USA, in 1983, and the Ph.D. degree from the Rensselaer Polytechnic Institute (RPI), Troy, NY, USA, in 1987, all in electrical engineering. He joined Tennessee Technological University, Cookeville, TN, USA, as an Assistant Professor with the Department of Electrical Engineering, upon his graduation from RPI, in 1987. He left Tennessee Tech, in 1993, as a tenured Associate Professor, to join Hanyang University. He is currently a Full Professor with the Electronic Engineering Department and the Dean of the College of Engineering, Hanyang University. He has published nine authored books and over 200 refereed technical articles in the areas of CATV, IPTV multimedia systems, and vehicle communication systems. He holds over 40 domestic and international patents. His research interests include in-vehicle networks, in-robot networks, and autonomous vehicles. He is a Life-Long Member of the Korean Information and Communications Society. He received the Initiation Award from the U.S. National Science Foundation, in 1990. He served as the Chairperson for the Digital Cable TV Steering Committee representing the Ministry of Information and Communications (MIC), from 2001 to 2005. He has been serving as the Chairperson for the Korea Digital Cable Forum, since April 2008.

• • •