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Evolution of machine intelligence for mobile robots

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Review

Evolution of machine intelligence for mobile robots

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Abstract—Active research and development is carried out for various mobile robots or robotic vehicles. This paper tries to find a new principle of the evolution of machine intelligence for robotic vehicles. The machine intelligence of robotic vehicles is the integrated ability composed of sensors, actuators, and computers, which produces the travel versatility of robots. Therefore, the relation between the performances of sensors, actuators, and computers, and the produced travel versatility was examined on 18 previously reported wheeled robotic vehicles with reference to the study on the evolution of vertebrate brains. The obtained hypothetical principles are as follows. Computer power varies in proportion to the summation of both rates of information input from sensors and information output to actuators for robots with the same grade of travel versatility. Robotic vehicles with a high grade of travel versatility have greater computer power than those with a low grade.

1. INTRODUCTION

Recently, intelligent mobile robots have been studied actively [1]. But what is an intelligent mobile robot? The term 'intelligent mobile robot' is often used to describe a future generation mobile robot capable of travelling anywhere and executing any instruction, which is only a dream today [2–4]. In the research for an intelligent mobile robot, the principal problem is to realize machine intelligence. However, the term 'intelligence' is not a physical or a technical term, but a psychological term [5]. Therefore, the target tends to be non-physical, non-qualitative and subjective in the research for an 'intelligent mobile robot'.

In this paper, the technical meaning of machine intelligence is analysed first, followed by a hypothetical principle of the evolution of machine intelligence for robotic vehicles.

2. MEANING OF INTELLIGENCE

2.1. Robotics, cognitive science

Tsuji [6] referred to robotics as having importance in functioning as a bridge between symbol-information processing, the essence of AI, and the real world. Nagata [7] interpreted machine intelligence of robots in terms of the function to perform a task or the ability to accept high-level languages.

With regard to cognitive science, Toda [8] has said that animals that make better use of emotions have considerable intelligent information-processing ability. He also stated that animal intelligence utilizes not discrete symbols, but fragments of sensory perception.

Moravec [9] interpreted, based on the consideration of animal evolution, that computer power is a key technology to build machine intelligence. He explained that computers with a speed of 10^6 MIPS might yield general intelligent machines exceeding the brain power of humans. He proposed a new interpretation of machine intelligence in which it is evaluated by the speed of computation.

These interpretations indicate the importance of examining animal intelligence in order to study machine intelligence for robotic vehicles.

2.2. *Zoology*

There have been only a few papers [10–12] discussing animal intelligence which give suggestions to the study of machine intelligence for robotic vehicles. Jerison [10] examined the relation between body weight and brain weight for various vertebrates. He found that the brain weight varies in proportion to the 2/3 power of the body weight (Fig. 1). The proportional coefficient is called the encephalon index. The encephalon index of higher vertebrates is large, while that of lower vertebrates is small. This relation is expressed as follows:

$$E = Ke\ P^{2/3}, \tag{1}$$

where E is the brain weight, P is the body weight, and Ke is the encephalon index.

Jerison explained that the brain weight was proportional to the body surface, since the sensory and motor surfaces of an animal were projected onto the structure of the brain. Therefore, the brain weight is proportional to the body surface. This indicates that the intelligence of an animal is related to the encephalon index, Ke. Therefore, the larger the value of Ke, the higher the intelligence level of the animal.

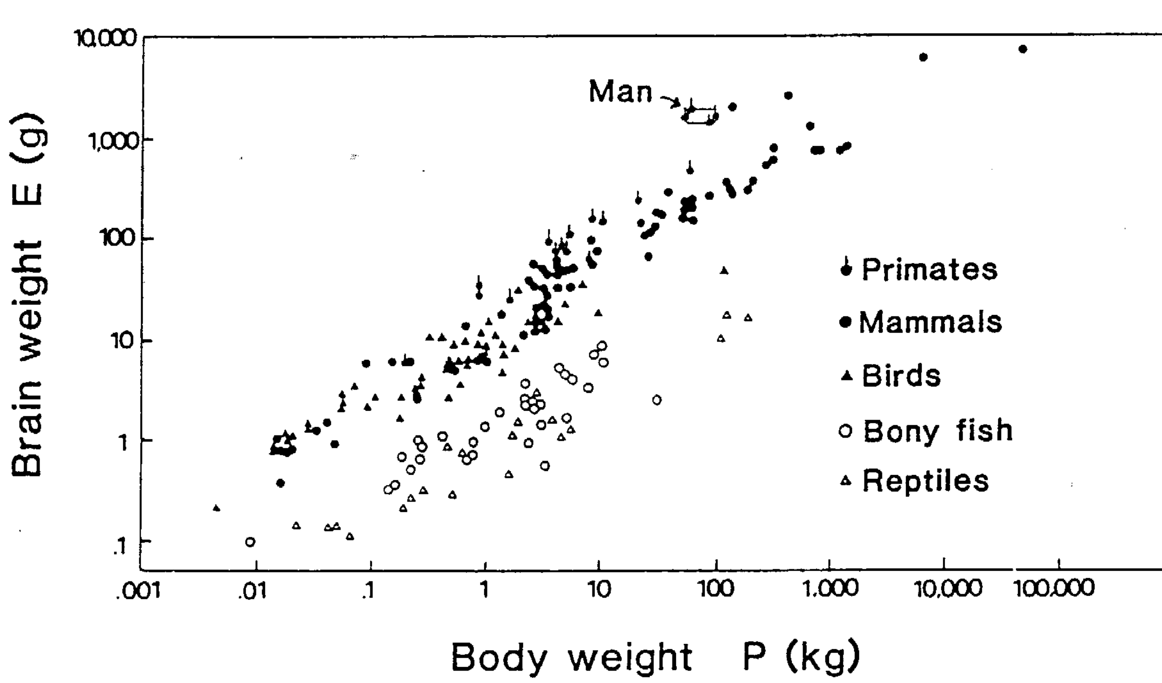

Figure 1. Relation between brain weight and body weight in vertebrates. This is a modification of the original figure in ref. 10 (Copyright © January 1976 by *Scientific American*, Inc. (All rights reserved).

3. MACHINE INTELLIGENCE FOR ROBOTIC VEHICLES

3.1. Basic idea

In this study, high-level machine intelligence for robotic vehicles is defined as the ability to adapt intelligently to any environment while travelling. To make a robot move in a clever way, the robot must be equipped with versatile sensors, high-power computers, and precisely controlled actuators.

(1) Sensors. High-resolution sensors can acquire travel information such as landmarks, and the distance and direction of obstacles of targets from the surroundings, which are necessary to decide the most suitable route adapting to current circumstances.

(2) Computers. High-power computers can plan a large variety of travel movements to suit the circumstances. Based on accumulated experience and estimation of the changes in conditions, such computers can process vast amounts of information which enables not only pre-programmed movements, but also movements adequately programmed adapting to current circumstances.

(3) Actuators. Precisely-controlled driving mechanisms or actuators enable the vehicle to move with high resolution and with a high degree of freedom, as planned by the above computers.

Machine intelligence for a robotic vehicle is regarded as the total travel ability determined by the relations between the performances of sensors and actuators, and computer power.

3.2. How to analyse machine intelligence

Applying Jerison's study to mobile robots, machine intelligence can be interpreted as follows. The surface of an animal's body is considered to represent the summation of all information sent by sensors distributed on the body surface, and that received by muscles distributed in the body. Therefore, the surface of an animal's body can be considered to be equivalent to the summation of all information sent by sensors (S) and that received by actuators (A) of a robotic vehicle. On the other hand, as the brain is a great mass of a vast number of neurons and a parallel processor [13], its information processing power may be proportional to its weight. Here, the information processing power is defined as the amount of information processed by a computer or a brain in a unit time. The brain weight is considered to correspond reasonably to the information processing power of a computer, namely, computer power (C).

The above interpretation leads to the idea of examining machine intelligence for robotic vehicles based on $(S+A)$ and C like Jerison's theory. However, it is not enough to discuss machine intelligence based only on $(S+A)$ and C for the following reason. Assuming that there are two robotic vehicles equipped with the same sensor, actuator, and computer, but only one of them is equipped with very sophisticated, though time-consuming software, then this one can travel only very slowly. In a practical sense, it may happen that the robot cannot move. On the contrary, the other robot with limited software can move quickly. It is necessary to take the difference in travel speed into consideration; it is no use discussing the machine intelligence of a non-movable robotic vehicle.

In order to make the robot travel at a planned velocity, the computer must complete reading the output of the sensor, planning the movement and sending the information to the actuator in a short time, determined in connection with the planned travel velocity (V). This process is repeated during the travel. Here, the information input rate of the computer is defined by the product of the frequency of reading the sensor output and the amount of information from the sensor. When the computer power is high enough compared with the information input rate, large sophisticated programs can run on the computer, enabling the robot to travel intelligently. Similarly, the information output rate of the computer is defined by the product of the frequency of sending the information to the actuator and its amount. Accordingly, similar consideration for the actuator leads to the same result. To analyse machine intelligence, the information input and output rates of the computer should be taken into consideration. In the following study, the repeat frequency is replaced by the travel speed, because a high frequency is needed for a high travel velocity and a low frequency is acceptable for a low velocity. Consequently, machine intelligence for robotic vehicles is interpreted by examining the relation between $(S+A)V$ and C as shown in Fig. 2. S, A, and C are examined in detail in the following section.

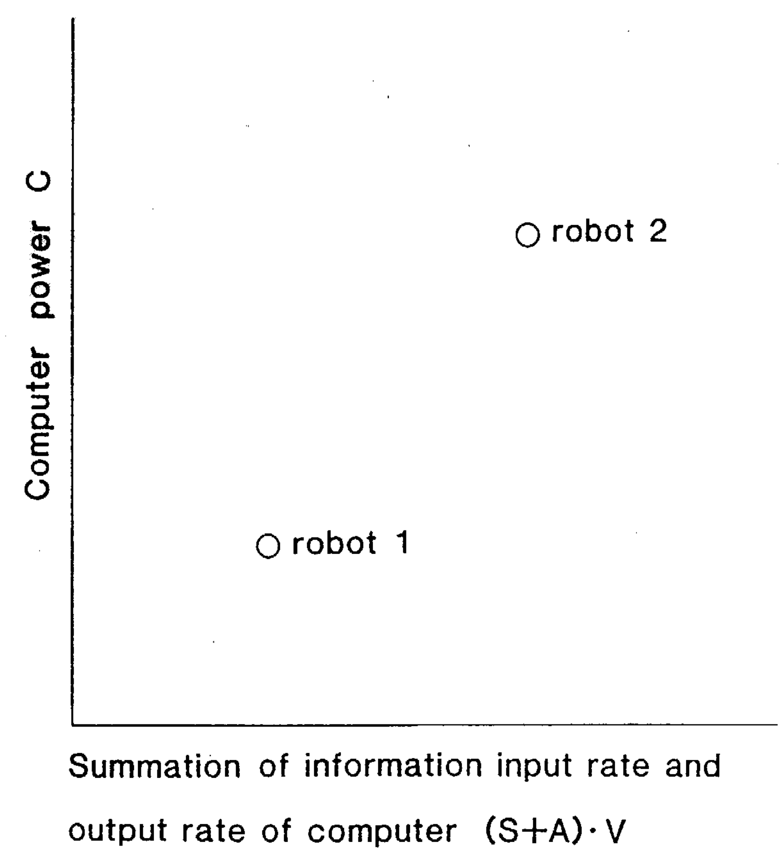

Figure 2. Method for studying the intelligence of a mobile robot based on the intelligence of vertebrates.

3.3. Sensors and actuators

S is an indicator of the acceptability of information from the surroundings, which is determined by the sort or number of sensors, and the number of their output levels. The value of S is obtained as follows. First, the amount of information generated by each sensor, i.e. the maximum number of quantized states of output signals from the sensor expressed in bits, is calculated. Then their summation gives the resultant S for the robotic vehicle (Fig. 3).

The amount of information received by the actuators, A, indicates the variety of movement of the robotic vehicle. The sort or number of actuators used in the robotic vehicle, and the number of their output force levels determine A. The value of A is calculated as follows. First, the amount of information sent to each actuator, i.e. the maximum number of digitized states of input signals to each actuator expressed in bits, is calculated. Then their summation gives the resultant A for the robotic vehicle (Fig. 3).

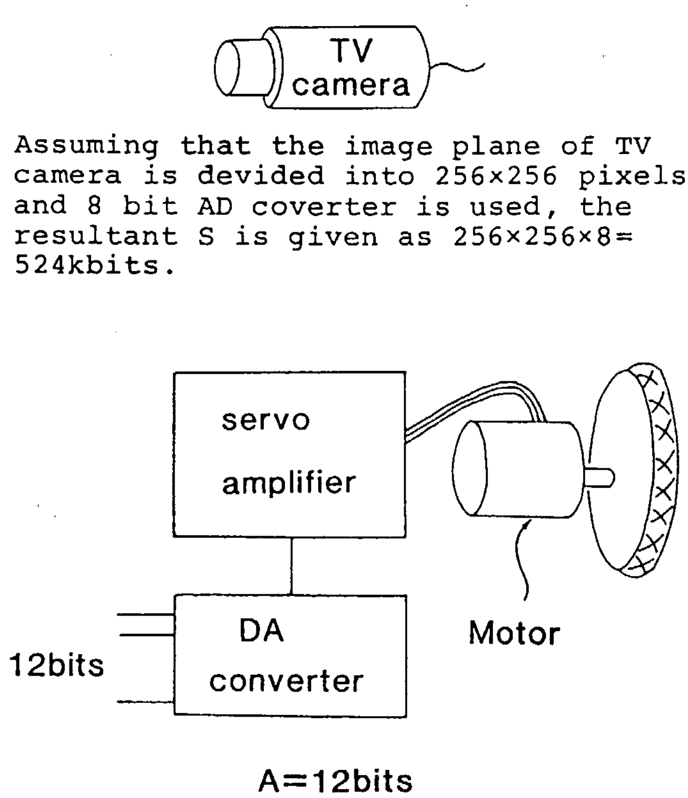

Figure 3. Calculation example of the amount of information sent by the sensor (S) and that received by the actuator (A).

3.4. Computer power

The power of a micro-computer [14] is examined in this section, because it is usually used as the principal information processor in a mobile robot. Computer power is influenced by its memory capacity in principle, but its main influence is the calculation speed. Therefore, only the calculation speed of a micro-computer is analysed. Three important factors affecting the calculation speed are considered:

(1) *Execution time of the instruction.* When the execution time of the instruction is reduced by half, twice the calculation speed is obtained.

(2) *Number of machine instructions.* The calculation speed of a computer with an instruction peculiar to each operation is higher than that of a computer without such a set of instructions. It is considered that a computer with many kinds of instructions has a higher calculation speed.
(3) *Machine word length.* When the machine word length increases, the computer power also increases. For example, in the case of 16-bit integer calculations using an 8-bit computer, the execution time increases empirically three or four times in the addition or subtraction mode, and six or ten times in the multiplication or division mode, compared with the execution time for a 16-bit machine. In the case of a real number operation, a similar difference in the calculation speed is observed between the two machines. As a result, it is considered in this paper that the computer power varies with the square of the word length expressed in bits.

These considerations lead to the following equation defining the computer power C:

$$C = \frac{(\text{number of machine instructions}) \times (\text{machine word length}/8)^2}{(\text{execution time of instruction})},$$

where (machine word length/8) means the length relative to a basic 8-bit word. The power of analogue circuit or a special purpose LSI will be represented by the computer power necessary to execute the information processing for the same purpose. When plural computers are used, the total computer power is estimated by their summation.

4. EXAMINATION OF EXAMPLES

In order to check the adequacy of the proposed interpretation, many available reports on robotic vehicles were reviewed. The vehicles were restricted to only wheeled or crawler-type machines. The values of S, A, and C were calculated from the data reported in the studies. However, when the necessary data were lacking in the papers, reasonable estimated values were adopted. The mean value of the execution time for various addition modes was used as the execution time of instruction to calculate C. The results obtained are listed in Table 1.

The results are also plotted in Fig. 4, in which the abscissa and ordinate are the total information input and output rates of the computers, and the computer power on a logarithmic scale, respectively.

Figure 4 shows that the total information input and output rates for vehicles 1, 16, 17, and 18 are greater than those for the other vehicles. This is because TV cameras are used in these machines, which generate a large amount of input information to the computers. Nevertheless, the computer power of the above four robots ranges from 10^3 to 10^7. This is because the computer powers differ greatly between the four machines: vehicle 1 uses a 16-bit personal computer; robot 16 utilizes a 16-bit micro-computer with a subsidiary special-purpose computer for image processing; machine 17 uses four work stations; and robot 18 uses a base computer VAX11 with 100 MFLOPS FPP, radio-linked to the robot itself. Furthermore, robot 18 is not an actual travelling machine but a theoretical machine

Table 1.
The mobile robots examined

No.	Name	V (m/s)	S (bits)	A (bits)	C ($10^3 \times 1/\mu s$)	$(S+A)\cdot V$ (bits · m/s)	Ref.
1	Image Guided Vehicle	0.2	524×10^3	$\simeq 20$	1.23	0.11×10^6	15
2	AGV	2.8	57	26	6.01	232	16
3	AGV	1.4	165	20	4.94	259	17
4	AGV	0.75	18	16	0.105	25.5	18
5	AGV	1.4	16	8	0.105	33.6	19
6	Yamabiko 3.1	0.5	80	40	0.12	60	20
7	Yamabiko 9	0.3	88	24	0.363	33.6	21
8	Meiji Univ. Micro Mouse	0.2	29	16	0.2	9	22
9	Mitsubishi Micro Mouse	0.2	30	16	0.095	9.2	23
10	Namco Micro Mouse	0.2	10	16	0.1	5.2	24
11	MELDOG MKIII	0.54	205	49	0.277	137.2	25
12	MELDOG MKIV	0.54	220	35	0.277	137.7	26
13	HERO I	0.3	33	64	0.06	29.1	27
14	Sweeping robot	0.5	114	24	2.46	69	28
15	ICAGV	0.2	27	24	0.242	10.2	29
16	Mobile robot	0.54	512×10^3	100–200	173	0.28×10^6	30
17	NAVLAB	0.10	6.4×10^6	$\simeq 40$	1.4×10^3	0.64×10^6	31
18	CMU rover	0.017	524×10^3	72	22×10^3	8.9×10^3	32

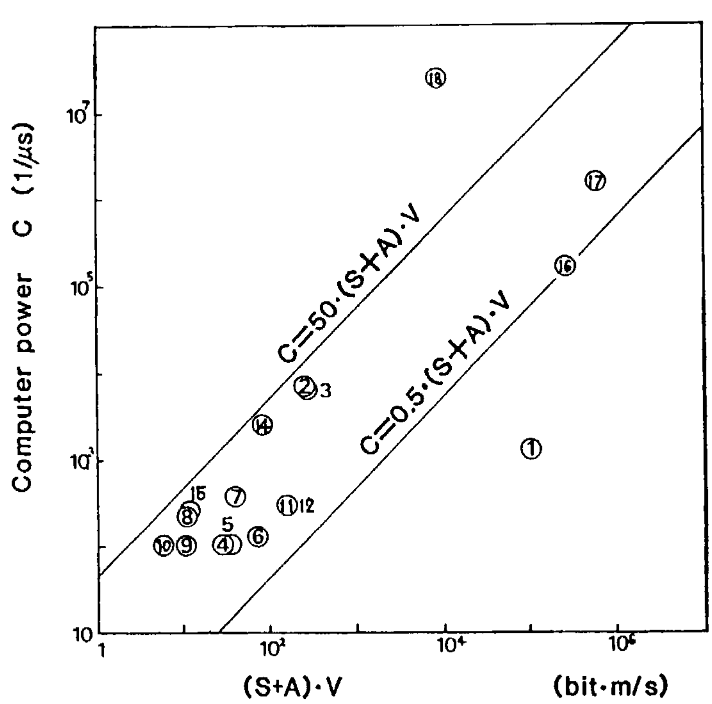

Figure 4. Relation between the computer power and summation of the information input and output rates of the computer used in the mobile robot. A small circle denotes each robot. The number in the circle identifies each robot listed in Table 1.

proposed by the designer of the robot. The other 14 robots are equipped with a sonar, an optical sensor, two or three motors, and an 8-bit or 16-bit micro-computer.

The following results are derived from Fig. 4:

(1) For vehicles 2–17, the data fall along a line with a slope of unity on log–log coordinates. This means that $(S + A)V$ is proportional to C for these machines.
(2) Robot 18 appears in the upper area of the above-mentioned line, which indicates a higher computer power. On the contrary, robot 1 is located in the lower area of the line, which indicates a lower computer power.

5. CONSIDERATIONS

Inspecting the examined reports in detail, it is possible to classify the travelling ability of each machine or robot to recognize landmarks and obstacles in the surroundings.

Robot 1 can travel only along a white line painted on the road surface. Its image-processing algorithm is especially developed to detect white lines. It does not work under other conditions.

Robots 2–17 can travel only in certain surroundings specified by the designers of the robots. They can travel along roads relying on the road surface colour or road boundaries, guided by white lines as a supplementary aid, or along corridors in buildings. They can also travel according to numerical data stored in the memory with or without slight modifications. In order to realize these types of travel, the machines are equipped with sensors such as sonars, optical range finders, and image processors for detecting landmarks, guides, and obstacles in the surroundings. These sensors are specially made to work effectively under the conditions of the predetermined surroundings specific to the robots.

The basic ideas implied by the robot designers are as follows:

(1) The designers decide what to select as a landmark or a guide from the vast amount of information in the travelling surroundings.
(2) The robotic vehicles are equipped with a specific sensor for detecting the predetermined landmarks or the designated guides.
(3) The robots which travel to their predetermined destination have on-board maps giving necessary information on the surroundings. The representation method of the map is determined by the robot designers.

Comparing robot 2–17 with robot 1, it can be considered that the former robots have more adaptability to the variation of travelling surroundings than does the latter robot.

Robot 18 can proceed to the destination on its own, selecting paths to avoid the obstacles detected by the present stereo machine vision. No special environmental conditions are predetermined for this machine.

The basic ideas are as follows:

(1) The designer does not specify the travelling places for the robot. This implies that neither a landmark nor a guide is predetermined by the designer.
(2) The robot is equipped with a sensing system to detect objects from the surroundings available as landmarks or guides.

Robot 18 has the best adaptability to various travelling environments.

These considerations lead to the interpretation that the machine intelligence level of robot 1 is the lowest and that of robot 18 is the highest among the 18 robots. This is the reason why robots 1 and 18 appear in the lower and upper areas of the plot in Fig. 4, respectively. Taking this into account, the equation on the machine intelligence of robots 2–17 can be given as

$$C = K(S + A)V, \tag{2}$$

where C is the computer power (in $1/\mu s$), S is the total amount of information sent by the sensor (in bits), A is the total amount of information received by the actuator (in bits), V is the maximum travel velocity (in m/s), and K is the proportional coefficient.

If equation (2) is also applicable to robots 1 and 18, the less environmental restriction there is, the larger the value of its K. Therefore, it is reasonable to say that the machine intelligence of mobile robots is reflected in K.

In Fig. 4, robots 2–17 are plotted along a line with a slope of unity, but their deviations from the line are not so small. Larger deviations weaken the reliability of the obtained hypothetical result. Therefore, the factors affecting the deviation must be analysed.

An animal is a balanced system without unnecessary abilities, completed by natural selection. This yields a good data scattering with only a little deviation as shown in Fig. 1. In the current state of mobile robots, on the other hand, many original forms of robots are being created. They have not yet reached the stage of evolution where only the most suitable ones survive by industrial selection. This yields imbalance in $(S + A)V$ and C, resulting in a high degree of data scattering as shown in Fig. 4. the effect of this factor has not yet been clarified.

As to the hardware available to make mobile robots, S, A, and C show only discrete numerical values. This also causes a high degree of data scattering in Fig. 4. This effect is examined in the following. Assuming that for the robots in Fig. 4, S, A, and C vary by a factor of 2–1/2, which is a typical variation step in digital techniques, it can be easily understood that the replotted new figure supports the obtained hypothesis even in the worst case of deviation. The effect of this factor can be expected to be small.

In addition, the effect of the numerical errors of S, A, and C are examined. Assuming that the S, A, and C values have relative errors of a factor of 2–1/2 in Table 1, it is clear from the same consideration that these errors scarcely affect the result.

6. CONCLUSIONS

This paper can be summarized as follows:

(1) Machine intelligence for mobile robots is analysed from the engineering point of view based on the analogy of the study on the evolution of vertebrate brains. This study yields the following hypothesis.

(2) For many current wheeled robotic vehicles, the computer power varies in proportion to the summation of information input and output rates of the computer.

(3) The less the restriction on the travelling environment for robotic vehicles (in other words, the more unknown the travelling space), the larger the magnitude of the proportional coefficient.
(4) The machine intelligence level of a robotic vehicle is determined by the relation between its sensing ability, its actuating ability, and its computer power. If a robotic vehicle has greater computer power in comparison with its sensing and actuating abilities, it can travel by adapting to a large variety of places, and, accordingly, we can say that its intelligence level is high.

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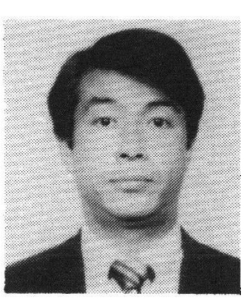

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