Timeline for development of functional autonomous walking robot to replace construction workers

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ABSTRACT

One conceivable solution to the current shortage of construction workers is to introduce autonomous walking robots onto construction sites. The author has investigated the best of the current generation of walking robots and concludes that the most important technological requirements for the development of such robots are computer hardware that imitates the human brain and deep learning of the type that enables human development. Four steps of robot technology are defined according to function and a likely timeline for the realization of each step is estimated by comparison with the development of human capabilities from fetus to adult.

1. INTRODUCTION

A shortage of indigenous workers on Japanese construction sites has long been predicted. Whereas in other countries such shortfalls have been met by bringing in foreign workers, this is not possible in Japan because immigration controls currently prohibit the entry of such laborers. It is assumed that this immigration regime will continue into the future, so the use of robots on construction sites is seen as a means to solve the labor shortage (which is predicted to amount to 470,000 people by 2040).

Unlike factories, construction sites present a situation where the work area changes daily, construction materials stored on the ground present obstacles to be dodged, rebars and similar materials need to be positioned and prepared by cutting, stairs have to be climbed, etc. Industrial robots that have been designed to operate in factories are unable to deal with such conditions. For construction sites, an autonomous walking robot is essential.

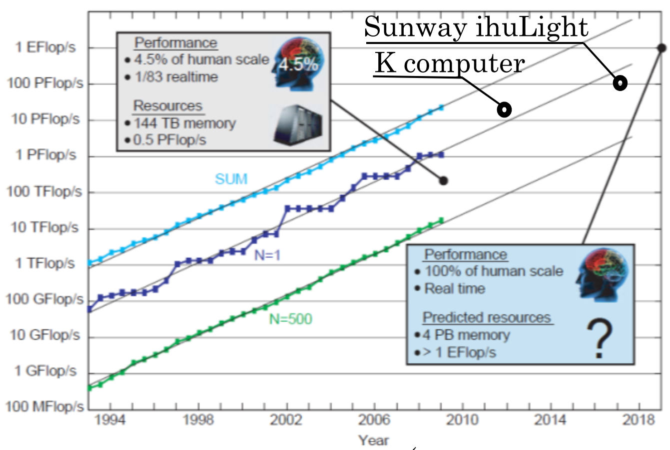
Reading about robot technology in the media, including articles about the technological 'singularity' that is a recent mass media buzzword, one might imagine that autonomous walking robots are just over the horizon. Meanwhile, even though information and communications technology (ICT) is advancing greatly on a day-to-day basis, it is still the case in construction that an engineer prints out drawings, which are the final result of ICT in everyday work, and then gives oral instructions to those who actually do the work. That is, manual labor is still done by humans. Why this last area of human manual labor remains and whether robots could automate it remain open questions.

Based on this background, the author (as chairman of the JSCE's Research

Sub-committee of Autonomous Walking Robot to Replace Construction Workers) investigated the most advanced autonomous walking robots in the world today: Asimo (Honda Institute of Technology) in Japan, RHP-2 Reform (AIST) in Japan and ATLAS (Boston Dynamics, Inc.) in the United States. The author's findings are that the development of autonomous robots depends on both hardware and software[1]. This document examines these two areas of development and considers when each function might be realized.

2. HARDWARE CAPABILITY

According to Moore's famous law, the density of components on computer chips doubles every two years. Although a limit to Moore's law has been predicted with each new generation of technology, so far continues to apply. If technology continues to advance at this rate, there are those who say that computers will surpass the capability of the human brain by 2025 and surpass the capability of all human brains combined by 2045. Supercomputer simulations of the brain's cortex[2] are illustrated at N=1 line in Fig. 1, including the newest data from 'K Computer' and 'Sunway ihuLight'[3]. As the figure shows, computers have yet to reach the performance of a human, but they have reached 4.5% of human processing capability in 1/83 real-time. In the case of 'K Computer', it has almost the same processing ability as a human, but consumes 12.6MW of electric power (equivalent to the consumption of 30,000 houses) [4] and occupies a volume of 1.29x107L (volume of computer building = 4,300m2 x 3m = 12,900m3 = 1.29x107L) [5]. On the other hand, the target power consumption of an autonomous walking robot is 1kW, equivalent to that of a human brain, and the desired volume is 2L. This means that consumption must be reduced to 1/13,000 and volume to 1/6,500,000. With current



Notes: With addition of the latest data (K computer and Sunway ihuLight)

Fig. 1 Cortex simulations by supercomputer[2] power consumption, if the volume could be reduced to 2L, the heat generated would melt the robot's brain.

In an attempt to overcome the issue of performance and heat generation by reverse engineering, DARPA is pursuing its SyNAPSE Program[6]. The human brain operates at 20Hz. On the other hand, the computer being used by the author operates at 1GHz. By getting a computer to operate at the same 20Hz as the human brain, the heat generation issue could be solved. Hence this effort entails structuring a computer similarly to the neural structure of the human brain. To realize such a simulation of the neural structure, deep learning software will be needed to support the hardware. A road map toward an autonomous walking robot able to replace a construction worker based on this approach is shown in Fig. 2. The neurons of rat and cat is planed to increase from 1,000,000 in 2013 to 100,000,000 in 2017. If this pace of development continues up to 2x10^{10} neurons, which is the human neuron count, performance and heat generation equivalent to the human brain will be realized in 2022 at the hardware level.

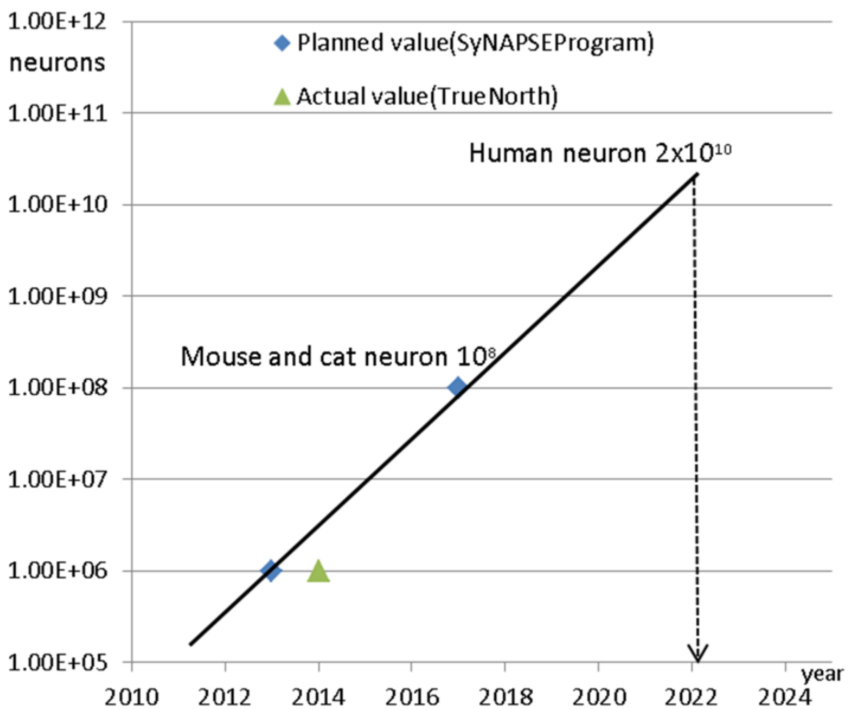


Fig. 2 Road map for replacement of human construction worker by autonomous walking

3. SOFTWARE CAPABILITY

In the field of artificial intelligence (AI), weak AI and strong AI are specific branches. Most AI researchers are fans of board games such as the Japanese game Go (igo) and their efforts are directed at improving AI capabilities in this area[7]. This is a form of weak AI and is something that computers are very good at. On the other hand, strong AI applies to everyday human activity in the form of manual work. For example, it might involve selecting a tool, conveying the tool from workshop to site, using the tool to cast concrete and adjusting the work process to suit site conditions.

In the 2 billion years since life began on earth, the brain has not developed to be particularly good at playing board games. However, it is well adapted to act, think and innovate in the world in which it finds itself. This is an ability that AI has yet to achieve.

In researching the ways in which robots are controlled, the author found that each motion is controlled by an individual program. The resulting motion is very smooth, but if the robot is faced by new circumstances, a new program is needed. For example, in the case of climbing construction scaffolding, each movement of a foot, arm, hand, or waist must be controlled by a new program. In envisaging that a robot that can move around a construction site, climb steps and scaffolding, cope with wet ground, and clamber over pipes, a separate program is needed for all conceivable cases for every site condition. The task is huge and very costly.

A more realistic approach is deep learning. With deep learning, a robot will develop capabilities through a form of self study.

Deep learning reminds the author of his/her own growth. Learning from parents and teachers is important, but self study and learning from experience is also very significant.

The teaching provided by parents and teachers might be seen as a main control program or operating system. Self study and experience is then what we call deep learning. Deep learning begins in the fetal stage of life. The fetus kicks against the mother's belly, getting feedback between brain neurons and leg motion and allowing a form of calibration. After birth, thumb sucking and observing the movement of an arm are also part of deep learning. While crawling, pulling themselves into a standing position, and taking first steps, infants' brains are studying motion and balance by deep learning as the arm and leg muscles grow.

The successful development of AI based on deep learning, which imitates the way the brain learns, is a crucial factor in replacing a construction worker with an autonomous walking robot.

4. COMPARING GROWTH OF THE HUMAN BRAIN AND THE DEVELOPMENT OF ROBOTS

The development of an AI robot will follow the growth steps of a child through the process of deep learning. The relationship between the stages of human brain development and motor skills, manual skills, emotions/language/social nature, and lifestyle are laid out in Table 1 to 4 [8) 9) 10) 11)], divided into the main developmental steps: fetus, up to one year old, infant (1 to 6 years old), child (6 to 12 years old), adolescent (13 to 19 years old) and adulthood. The table shows the large and small of difficulty of realizing each function. For example, the infant' s ability to walk alone (motor skill in Table 2), which corresponds to the ability of a robot to walk on two legs, is realized at around 12 months and knowing the mother' s face (others in Table 2), which corresponds to current levels of image recognition, is realized in infants of 4 months. Therefore walking on two legs is more difficult for a robot to achieve than image recognition.

The author has divided into four steps the development of autonomous walking robots able to replace construction workers, as follows.

(1)Step 1: Robots travel along worker access routes carrying lightweight items.

(2) Step 2: Robots work alone to do concrete compaction work using a vibrator.

(3) Step 3: Robots collaborate to do concrete compaction work using a vibrator.

(4) Step 4: Robots are capable of responding to discrepancies between drawings and actual site conditions as well as other unexpected situations (works manager)

Looking at the functions required at each robot development step and comparing them with the motor skills, manual skills, emotions/language/social nature, lifestyle, and other aspects of human growth laid out in Table 1 to 4, those items relating to the robot development steps are extracted as shown in Table 5.

Table 1 Relationship between the stages of human brain development and motor skills, manual skills, emotions/language/social nature, and lifestyle (Fetus) [8) 9) 10) 11)]

	Fetus										
	0 Week	7W	10W	16W	17W	20W	21W	22W	26W	30W	38W
Brain development	Cell division commences	Neurons begin to differentiate in the cerebrum. Differentiated neurons form information networks with other neurons via dendrites for receiving information from other neurons and axons for conveying information.	Fetus grows to 7 cm in length. Neurons of the spinal cord extend to the ends of the limbs and combine with the muscles.	Optic nerve associates with the cerebrum; it becomes possible to discern visual information.	Production of neurons in the cerebrum approaches completion, and about 14 billion nerve cells form the cerebral cortex. The number of neurons in the cerebrum peaks at this time; from now on it will decrease throughout the lifetime.	"Myelin sheath" begins to form in the axons of mature neurons (myelination).Conduction efficiency of electric signals in the brain is remarkably enhanced. After myelination, brain function development for linking nerve cells and completing signal transmission/processing functions starts.	The inner ear is wired to the cerebrum and the auditory nerve; hearing information processing, which senses sound, starts to function.	In the brainstem, myelination also begins in sensory nerves such as the trigeminal nerve, auditory nerve, inner ear nerve and the like related to the eye and jaw following the eye nerve and facial nerve.	The large framework of the cerebrum, which characterizes humanness, is formed. Brainstem also approaches completion	Total length of the fetus is about 45 cm. The nervous system, too, is minimally prepared for birth. The system for hearing sounds from the outside world (hearing) is completed. Light signals are transmitted into the brain.	At 38 weeks, the human brain that has evolved over 500 million years is fully formed.
Motor skills			Active exercise in the womb						Reflex response to sound and light and movement leading to breathing		
Manual skills	-	-	-	-	-	-	-	-	-	-	-
, language and social nature	-	-	-	-	-	-	-	-	-	-	-
Lifestyle	-	-	-	-	-	-	-	-	-	-	-
Others	-	-	-	-	-	-	-	-	-	-	-

Table 2 Relationship between the stages of human brain development and motor skills, manual skills, emotions/language/social nature, and lifestyle (infants) [8) 9) 10) 11)]

infants (0 years old)	Brain development	Motor skills	Manual skills	Emotions, language and social nature	Lifestyle	Others
0 Years old Birth	of that of an adult's brain. The number of brain cells is almost the same as in an adult. Although the brain cell count is that of an adult, the fact that equivalent behavior and actions are not possible is because nerve cell development is immature. The brain has not learned and experienced enough.	Smiling starts. The infant will exhibit a special reaction to the mother's voice and fragrance only. (At 5 days) When the mother speaks, a smile is returned. (At 2 weeks)	Can grasp what is touched	–	–	–
1Month	–	–	–	Laughing in appreciation When his mother speaks, he starts to vocalize with joy.	–	–
2M	–	–	Grab a rattle	predicts moving out of the body and expecting others to respond. Emotions such as happy and sad can be	–	–
3M	Neurite development of the medulla oblonga-bridge	On finding the mother's nipple, for example, there is a reaction such as drinking. The neck can be held upright.	–	there or not. When his mother speaks, he becomes vocal with joy.	–	–
4M	Neurodevelopment of the midbrain	Turning over crawling on all fours, and sitting become possible. There is a straightening reflex, in which the body attempts to return to a straight attitude when tilted. Can sit if supported.	Shake the rattle. Grab spontaneously. Hold object in both hands	–	Can use a spoon.	Recognizes the mother's face.
5M	–	Able to turn over Able to sit without support	Can swap something with someone	Uses baby words with others.	Can take biscuits.	–
6M	Cerebral neurodevelopment	An "equilibrium reaction" begins in which the body is balanced to maintain posture. It is possible to stand and hang onto something for support, walk, and perform complex behavior and activities.	–	Dissatisfaction is expressed through crying. Fear also grows. Shyness.	–	–
8M	The density of synapses reaches a maximum.(8 to 9 months). The number of synapses will subsequently decrease to around 60% to 70% of this level in a few years.	Crawl Stand and hang onto something for support	Bring building blocks together with both hands	–	–	Significant development in intelligence is seen. Simple statistics and probability can be understood.
9M	–	Can hold on	Pin something small with thumb/index finger	Jealousy is expressed. Relationships between things can be seen from the viewpoint of others (such as themother). Able to say goodbye. Imitation of adult behavior.	–	–
10M	–	Can walk with help	Put things in and out of a box	–	–	object continues to exist even when not visible (persistence of objects).
11M	–	–	Scribble	Can say papa, mama etc. Pointing.	Can pick up a cup and drink.	Can understand and memorize a causal event chain.
12M	–	Can walk alone	Can grip small things between thumb and index finger	Use of words as a means of communicating will and emotion; episodes of crying decrease.	–	–

Table 3 Relationship between the stages of human brain development and motor skills, manual skills, emotions/language/social nature, and lifestyle (infants1to6) [8) 9) 10) 11)]

infants (1 to 6 years old)	Brain development	Motor skills	Manual skills	Emotions, language and social nature	Lifestyle	Others
1 Year	-	-	-	Can express requests by pointing. Uses one-word sentences (such as" Mama "). Stronger social behavior.		Independence and stubborn conflict with own emotions and inexperience of words. If another person is looking for something different from himself, it will become apparent. Understands that a picture is simply a representation of something. Based on statistics and probability, it becomes possible to infer human preference.
2Years	By the age of 3 years, myelination of sites related to the essential human movements is complete.	Can make two-leg jump (named goo jump). Can roll over on mats etc (cormorant gourd). According to music, he can walk faster, slowly walk, run and stop. Can climb, cross and get off his mother's hand with a table with a height such as the balance beam.	Holding scissors correctly and making a straight cut of about 2 cm. Cut a piece of origami by hand . (At this age, left and right hands cannot yet be moved back and forth.) Roll up origami. He is interested in building blocks and can stack five pieces high.	Interested in friends and can spend time with them without resistance even if his friends come next. Uses words and gestures necessary for play ("please do", "give me", "thank you"). Can answer simple questions about name/age/ etc. Replies on being called by name. Daily greetings ("good morning", "hello", "thank you", "good night"). Can talk and listen while making eye contact.	Attempts to use a spoonfork without help. Takes off socks and shoes without help. Can wash own hands. Remembers having slept. (remember sleeve roll)	Can imitate the same words by memorizing words pronounced as "apples". Can follow which upturned cup contains sweets.
3Years	The human brain, which is now about 80% complete, has a remarkable ability to develop language, especially in girls, due to the development of language centers.	Can make two-leg jump (named gooper Jump). Can walk, run, stop, and canter according to music. Can climb, cross, and get off the balance beam alone.	He can hold the scissors correctly and make a straight cut of about 5 cm. He can pick up glue, spread it on paper and stick things together. He can do an origami half-fold (Δ, □). He is interested in building blocks, can imitate shapes with about five pieces and repeat. He is interested in puzzles and can complete a picture consisting of 2 to 4 pieces, a shape consisting of 2 pieces.	Can distinguish between reality and imagination (objective and subjective), and begins lying as he can understand that others have erroneous recognition. Interested in friends and can play with them without resistance even if his friends come next. Can use the words necessary for play ("let me in", "please lend me", "please do", "please give me", "thank you"). Aware of manners in public places (keeps quiet, does not run). Touches concrete things and expresses characteristics in words (hard, soft, fluffy, rough, etc.).	Attempts to use chopsticks without help. Can change out of pajamas without help. Can fasten three or so front buttons (large) and snap fasteners. Attempts to correct inside-out clothes. Can remove shoes without help and attempt to put them on.	Females chat and have excellent communication. Males are superior in spatial cognition and are more theoretical. He can remember and express words such as "apples, bananas" "3, 6" in order. If it is 2 to 3 pieces, he will be able to memorize. Prepare three bowls and prepare two kinds of items that are about the size to enter the bowl. Show me where to put in the bowl and memorize what is in which bowl. It is possible to think about people, things and events that are not actually (physically) present. Can hold scissors correctly and make a straight cut of about 5 cm. Can pick up glue, spread it on paper and stick things together. Can do an origami half-fold (Δ, □). With the development of "symbolic thinking", it becomes possible to understand the relationship between a miniature room and the real room. Able to understand simple causal relationships. Self-concepts in behavioral aspects, such as "I eat rice every day", "I can run fast" begin to form. Begins to notice that the essence of things does not change even if their appearance does. For example, understands that an apple before peeling and an apple after peeling are the same thing.
4Years	Two major changes start to occur in the brain. One is a change in response to neurotransmitters , and the other is a change in neurotransmitters . With these changes, unnecessary connections between nerve cells are eliminated and one output is possible for one piece of information (input).	Can make two-leg jump (named kenpa jump). Can move forward on a mat etc. Walking normally on a balance beam without help at typical table height. Imitating gymnast.	He can grasp scissors correctly and carefully cut a circle about 10 cm in diameter. He can have fun using glue or sellotape. He can fold 2 or 3 origami. Interested in building blocks and understands the existence of hidden building blocks. He can have a topic. He is interested in puzzles and can complete pictures consisting of 4 to 12 pieces, shapes consisting of 2 to 3 pieces.	In terms of thinking, will understand that others have a different and unique mental world. As a result, interpersonal communication also becomes complex. In addition, it becomes possible to understand others psychologically. Morality and social interaction learned by involvement with friends, mainly through playing. "I have a brother", "I have a lot of friends", and similar phrases refer to relationships with surrounding people. Interested in friends and can get along well with them. Can understand orders and is able to wait. Can answer questions such as name, age, birthday, and so on. Can express intentions with words. Can create a story by observing a picture. Can search for same head word and same tail word . Touches concrete things and expresses characteristics in words (hard, soft, fluffy, rough).	Detaching clothes and closing down clothes . Can put on socks and shoes without problem.	Able to distinguish between biological phenomena and physical phenomena and understand their respective properties. The distinction between the subjective world and the objective world is not yet clear. Can remember the name of characters in a picture book, the order of the things that appear in a story, and so on. Has the memory ability to remember where something is hidden among four upturned cups.
5Years	-	Can run in a zigzag. Can move forward and roll over mats etc. Can climb the jungle gym. According to music, march, run, stop, skip, canter, bear walking, crocodile walking.	Correctly use various tools such as scissors (cutting lines, curves, oblique lines), stapler, punches, stick glue etc. Folds origami and can reason about the figure configuration. He can knot string and tie a ribbon.	Interested in friends and can make good friends autonomously. Has fun playing.Aware of manners in public places (understanding of morals). Answers questions such as name, age, birthday, address, telephone number, kindergarten, parents, seasons etc with phrase such as "Yes, it is ~". Can express intentions with words in the form of sentences. Can look at a picture and express mimetic words and onomatopoeic words in words. (Such as zaser, shikushiku, fluffy etc.) Can create stories by observing two pictures.	Can eat using chopsticks. Can clean up food spills. Can use and squeeze out cloths and towels. After taking off shoes, can put them away in good order.	Can memorize three elements of picture, position, color, picture, talk. Can remember the locations of three toys under five upturned cups after moving them around. Can draw a stick figure. Can understand a series, Can understand with concrete things and prints .
6Years	–	Can jump from a height of about 70 cm. Can climb to the top of the jungle gym.	Can knot string, tie ribbons, present ties , you can solve it. Can bundle with things with a rubber band. Can complete about five different origami figures	While playing, can make rules of play. Can read and write woads. Can gather tongues, collect tail words, and play "shiritori" with rules. Can write name correctly. Can understand opposites (bright ⇔ dark, up ⇔ down, raise ⇔ receive , close ⇔ open etc.) Can create stories by observing four pictures.	Can wipe it with a handkerchief to properly wash his hands .Can understand events. Can understand the days of the week. Can read the calendar. Can read the time. (○ hour, ○ hour and 30 minutes)	Can reason about the figure configuration. Understands the existence of hidden building blocks. Can make prints . Understands position from any orientation, including mirror images, the rotated images.

Table 4 Relationship between the stages of human brain development and motor skills, manual skills, emotions/language/social nature, and lifestyle(children, adolescents and adulthood) [8) 9) 10) 11)]

		Brain development	Motor skills	Manual skills	Emotions, language and social nature	Lifestyle	Others
children	6Y to 12Y years	Synapses, which are the joints between nerve cells, show a tendency to decrease after rapidly increasing from 1 to 3 years old. The period between these phases is used to flexibly change neural circuits to complete the brain foundation and is called the "susceptibility period" (critical period). Depending on ability and the particular function, it may be difficult for development to occur after this period. In the case of humans, the susceptibility period means that many abilities and functionalities arise around the age of 9.	−		By entering the world of written language from the world of only spoken words, the range of action widens. Selfishness decreases and simple logical thinking becomes possible. Through peer relationships in groups, the ability to read the minds of others (= understanding others' intentions, desires and emotions) is improved. Begins to understand the meanings and meanings behind norms and regulations. Participates actively in collective activities and collaborates.	−	After the 3rd to 4th grade of elementary school, the number of children who cannot keep up with the classes increases as the content becomes more sophisticated. Educational institutions call this "the wall at 9 years old. In Japanese language, good reading ability and writing skills, and in mathematics understanding of fractions, decimals, ratios etc. are the main tasks. In science, the power of invisible abstract thought, such as understanding electricity and magnetic force, becomes necessary.
adolescents	13Y to 19Yyears	In the "parietal lobe" and "temporal lobe" related to sensation etc., reorganization of the neural circuits is complete. On the other hand, reorganization of the "prefrontal cortex", which is responsible for thought and creativity and which controls complicated cognitive behavior, continues. Androgens in male hormones stimulate the "amygdala" and "hypothalamus".	−		An adolescent young person lack judgment or become emotional .	−	Physical development and change occur suddenly. From the viewpoint of intelligence, development of abstract thinking ability and scientific reasoning will be seen. Self-consciousness gets stronger, and conflict between self-consciousness and the actual situation becomes apparent. Has a strong sense that the present time has continuity with the past and future. Young people reconstructs new values by rejecting or reconfirming their values and judgment standards with reference to the values and philosophies and beliefs of friends, and become independent from parents. The aggressiveness of men seen in adolescence is related to the stimulation of androgen of the androgenic hormones, such as controlling the "amygdala" emotion of the limbic system and the inside of the ventral part of the "hypothalamus". Aggression leads to motivation created by substances in the brain of the amygdala and hypothalamus "noradrenaline" which leads to "fear" and "anger".
adulthood	Bbeyond 20Y years	Connections between nerve cells continue to develop even after the sensitivity period of childhood, and the network of cranial nerves is generally complete by the time adulthood is entered. However, after that, a new network of cranial nerves is formed by learning and experience, and the brain continues to grow. The brain's ability to change over a lifetime is called "brain" plasticity. In human beings, the skills of elderly skilled craftspeople, for example, are said to be an ability acquired as a result of the plasticity of the brain.	−	Skilled artisans have the ability to acquire "skills" from many experiences and handle problems in an optimal way. This can be said to be an example of crystalline intelligence where learning and accumulation of experience is utilized.	−	−	Human "fluidity of intelligence" peaks in adults about 50 years after birth. " fluidity of intelligence" is ability related to the speed and capacity for memorizing information and is not much affected by learning and experience; that is, it is intelligence used for processing information, so to speak. "Crystalline intelligence" peaks about 60 years after birth. Crystalline intelligence is the ability to process tasks using knowledge accumulated and structured through experience and learning so far.

Table 5 Comparison between the process of human growth and each step of robot development

Note: the four steps of robot development are —(1) carrying lightweight items along worker access routes, ----(2) working alone with a concrete vibrator, -·-(3) working in collaboration with vibrators and -··-(4) works manager

	Fetus (robot functionality assumed by 2022)	Infant (0 years old) (robot functionality assumed by 2022 to 2034)				Infant (1 to 6 years old) (robot functionality assumed by 2034 to 2039						Child (robot functionality assumed by 2039 to 2045)	Adolescent (robot functionality assumed 2046 to 2052)	Adult (robot functionality assumed beyond 2053)
	0 to 38 Week	Birth to 3Month	4M	5 to 11 M	12M	1 Year	2Y	3Y	4Y	5Y	6Y	6Y to 12Y	13Y to 19Y	beyond 20Y
Motor skills					(1) Walking alone				(2) Walking normally on a balance beam without help at typical table height. (2) Imitating gymnast	(3) According to music, march, run, stop, skip, canter, bear walking, crocodile walking				
Manual skills					(1) Can grip small things between thumb and index finger		(2) Can hold scissors correctly and make a straight cut of about 2 cm.		(3) Interested in building blocks and understands the existence of hidden building blocks.					(4) Skilled artisans have the ability to acquire "skills" from many experiences and handle problems in an optimal way. This can be said to be an example of crystalline intelligence where learning and accumulation of experience is utilized.
Emotions/language/social nature							(1)(2) Uses words and gestures necessary for play （" please do"，"give me"，"thank you"）.	(3) Can use the words necessary for play ("let me in", "please lend me", "please do", "please give me", "thank you"). (3) Touches concrete things and expresses characteristics in words (hard, soft, fluffy, rough, etc.).						
Lifestyle							(1) Takes off socks and shoes without help.		(2)(3) Can put on socks and shoes without problem.					
Other			(1)(2) Recognizes the mother's face.				(3) Can follow which upturned cup contains sweets.	(3) It is possible to think about people, things and events that are not actually (physically) present.						

Step 1: Robots travel along worker access routes carrying lightweight items.

A typical worker access route is shown in Fig. 3.

Motor skills: A robot walking on two legs corresponds to the ability of an infant of 12 months to walk alone.

Manual skills: Carrying lightweight items corresponds to gripping small things between thumb and index finger, which an infant of 12 months can do.

Emotions/language/social nature: Meeting on a walkway and giving way corresponds to the use of necessary words and gestures to play ("please do" , "give me" , "thank you") by an infant of 2 years.

Lifestyle: A robot able to switch attachments by itself (ex. foot attachments) corresponds to an infant of 2 years taking off socks and shoes.

Others: Recognition of humans and objects by a robot corresponds to an infant of 4 months recognizing the mother's face.

With regard to motor skills, the author considers that the technological level of a robot walking on two legs corresponds to an infant of 12 months walking unaided. At first glance, this is reasonable. However, a robot (which might cost over 1 million US dollars) will suffer damage if it falls, while an infant takes a passive stance as in judo and probably ends up with just a scratch and can pick itself up. This ability of an infant is a result of deep learning during the development of crawling and walking.

Fig. 3 Using a worker access route

Step 2: Robots work alone to do concrete compaction work using a vibrator.

Compaction work by one person using a vibrator is shown in Fig. 4.

Concrete compaction work can be considered the task of carrying the vibrator tool to the correct location and working alone in that specific place.

Motor skills: A robot able to walk on the re-bar mesh, still-fresh concrete etc. and to turn around in small spaces corresponds to an infant of 4 years walking normally on a balance beam without help at typical table height and imitating a gymnast.

Manual skills: A robot able to carry a vibrator and insert it into the correct position corresponds to an infant of 2 years holding scissors correctly and using them to make a straight cut of about 2 cm.

Emotions/language/social nature: A robot that meets human workers in the work area and yields to human workers corresponds to an infant of 2 years using the words and gestures necessary to play ("please do", "give me", "thank you").

Lifestyle: When a robot moves between still-fresh concrete and a metal access route, it must change its foot attachments. This corresponds to an infant of 4 years putting on socks and shoes without problem.

Others: A robot that can distinguish between humans, objects and different floor surfaces corresponds to an infant of 4 months recognizing the face of its mother.

However, when operating with others in the same area, it is highly likely that a robot with this level of development could get its foot entangled in a wire or similar and fall down.

Fig. 4 Concrete compaction work by one person

Step 3: Robots collaborate to do concrete compaction work using a vibrator.

Collaborative concrete compaction work using vibrators is illustrated in Fig. 5.

This task can be considered to be carrying the vibrator tool to the correct position and working in collaboration with others to compact the concrete.

Motor skills: A robot that can walk on still-fresh concrete etc., turn in small spaces and operate collaboratively corresponds to an infant of 5 years who can march, run, stop, skip, canter, walk like a bear and walk like a crocodile to music.

Manual skills: A robot witch can understand that hidden wire from view is connected to remain standing without a hidden wire tangled around its foot corresponds to an infant of 4 years interested in building blocks and understanding the existence of hidden building blocks.

Emotions/language/social nature: A robot that can operate collaboratively and communicate with others about the state of concrete corresponds to an infant of 3 years who uses the words necessary for play ("Let me in", "please lend me", "please do", "please give me", "thank you") and who is able to touch objects and characterize them in words (hard, soft, fluffy, rough, etc.)

Lifestyle: When a robot moves between still-fresh concrete and a metal access route, it must change its foot attachments. This corresponds to an infant of 4 years putting on socks and shoes without problem.

Others: A robot that is able to understand abstract instructions by another worker corresponds to an infant of 3 years thinking about other people, objects and events that are not actually (physically) present.

Fig. 5 Collaborative compaction work using vibrators

Step 4: Robots are capable of responding to discrepancies between drawings and actual site conditions as well as other unexpected situations (works manager).

A robot at Step 4 corresponds to a skilled artisan who has the ability to acquire skills from varied experiences and handle problems in an optimal way. This can be said to be an example of crystalline intelligence where learning and accumulation of experience is utilized.

5. SUGGESTED TIMELINE FOR REALIZATION OF EACH STEP

Author suggests a timeline for the realization of each step in robot development in Table 5 assuming time axis of the outline.

The human brain, which has been developing for 500 million years, takes shape in the fetus by 38 weeks old. By the first year of life, the infant has the same number of neurons as an adult. Authentic deep learning begins, resulting in connections and disconnections among neurons as various functions are realized. These first months of life correspond to the time beyond 2022, when robots will achieve the same number of neurons as a human, according to assumptions drawn from the SyNAPSE Program. (Refer to Fig. 2.)

If we assume that a year of robotics development beyond 2022 corresponds to one month of infant development, the first year of an infant's life equals 12 years in robotics. Robots can be expected to have the characteristics of a one-year-old infant by 2034.

Beyond, we can assume that deep learning will accelerate and the speed of robotics development will equal that of a child. This would make the robot equivalent to a child of 6 years in 2039, the beginning of adolescence in 2046 and the beginning of adulthood in 2053.

Mortar skills, manual skills, emotion/language/social nature, lifestyle, others corresponding to the robot at each step are connected with dotted lines in Table 5. Hence the most right time is the realization time of robot at each step.

Step 1: Robots travel along worker access routes carrying lightweight items.

Robot corresponds to infant of 2 years and is assumed to be realized in 2035.

Step 2: Robots work alone to do concrete compaction work using a vibrator.

Robot corresponds to infant of 4 years and is assumed to be realized in 2038.

Step 3: Robots collaborate to do concrete compaction work using a vibrator.

Robot corresponds to infant of 5 years and is assumed to be realized in 2039.

Step 4: Robots are capable of responding to discrepancies between drawings and actual site conditions as well as other unexpected situations (works manager)

Robot corresponds to adult beyond 20 years old and is assumed to be realized beyond 2053. Realization will be a long process.

6.CONCLUSION

A timeline for autonomous walking robots being able to replace human construction workers is set out by the author in terms of computer hardware and software development relating to deep learning. Four steps in the development of such robots are outlined by drawing a parallel with the process of human development through deep learning, including the required functions and the year in which they are expected to be realized. Step 1 is a robot that travels along worker access routes carrying lightweight items. This corresponds to an infant of 2 years and is assumed to be realized by 2035. A Step 2 robot can work alone to do concrete compaction work using a vibrator. This corresponds to an infant of 4 years and is assumed to be realized by 2037. In Step 3, robots will collaborate to do concrete compaction work using a vibrator. Such a robot corresponds to an infant of 5 years and is assumed to be realized by 2038. The final step, Step 4, represents robots that are capable of responding to discrepancies between drawings and actual site conditions as well as other unexpected situations (works manager). This corresponds to an adult over 20 years old and is assumed to be realized beyond 2053. Realization of this step will be a long process.

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