bipedal robot

A robot that mimics humans and walks on two legs

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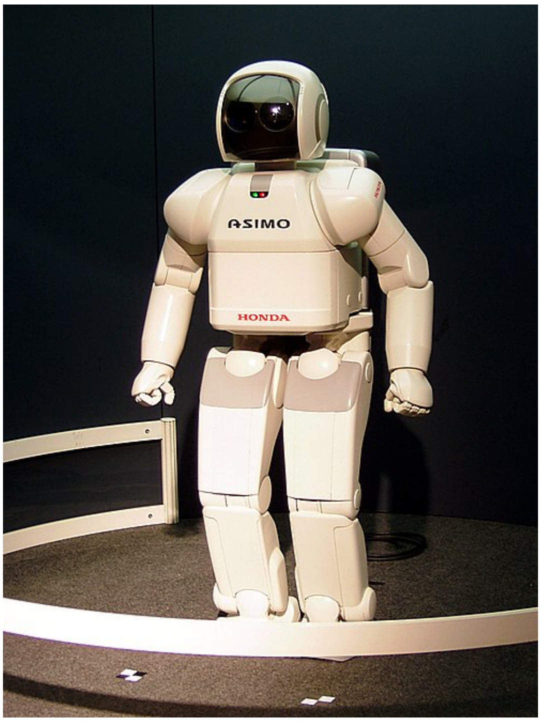
A bipedal robot (Nisokuhoko robot, *Biped walking robot* or *Biped robot*) is a robot that walks while balancing on two legs like a human being . Robots that have a shape similar to humans are called humanoids , but not all humanoids are bipedal robots.



ASIMO

A foot (leg) is a serial link mechanism consisting of two or more links connected by a rotating mechanism, and a biped robot has two legs. The world's first bipedal walking robot was WAP-1, developed in 1969 by Ichiro Kato of Waseda University . Honda 's P-2 (later ASIMO) , announced in December 1996, gave people a big shock [1] [2] [3] .

Purpose of bipedal robot research

Tea Serving Doll , British Museum

Bipedal robots are being researched with the aim of allowing them to move and work without hindrance in spaces that are primarily intended for human activity [4] [5] [6] .

There are also cases where the purpose is to have robots operate machines that assume human feet as user interfaces , such as car pedals, bicycle pedals, and foot-operated air pumps . Some of the early bipedal robots were created for the purpose of researching and elucidating the mechanism of human bipedal walking from an engineering point of view. In addition to walking on two legs, there are robots that do not have a means of movement, such as industrial assembly robots, on the ground (wheels , caterpillars , snake-like multi-joint structures, four legs, six legs), and underwater (unmanned submersibles). , in the air (unmanned aircraft), and in space (unmanned spacecraft).

Bipedal robot research and cultural background

The word "robot " is derived from the 1921 sci-fi novel "RUR" by Czech writer Karel Čapek, an artificial human named robot. In this novel, robots are depicted as slaves, and one day they rebel against humans and start killing humans. According to the description in the original text, robots are slaves of androids who harm humans. You can understand that many of the robots that appear in Hollywood movies have inherited this image from the original. It is also worth noting that rob- is not a good spelling in English , German , Slavic languages , etc., as a cultural context. (e.g. English robber: robber, thief, perpetrator rob: to rob, Slavic to rob раб: slave работа: labor)

In robotics research in Japan, several intellectuals have pointed out the cultural connection with karakuri [7] . In addition, the admiration for robots that act with and like humans, such as those depicted in manga and anime such as Astro Boy and Doraemon, has also led to research into humanoids and bipedal robots in Japan . Many people point out that this is one of the reasons why it is popular [8] . In fact, not a few robot researchers express such an opinion [9] .

industrialization

Although bipedal robots have long been highly regarded both domestically and internationally for their high technological prowess and originality, they are still far from being industrialized [Practical use of new technologies such as bipedal walking robots requires steady improvements, not epoch-making ideas by geniuses. It has been pointed out that there is no [10] .

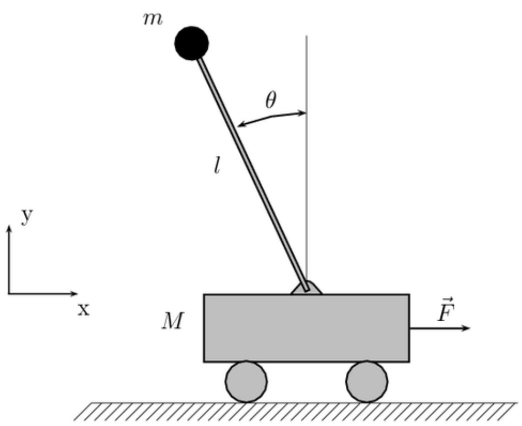
application

Kawada Industries , which developed HRP-2, is closely related to aircraft control technology, such as applying the control technology acquired in the development of unmanned helicopters [11] .

The control technology for bipedal walking robots is common to personal mobility vehicles and powered suits . For example, Honda's U3-X and weight-bearing walking assist systems apply ASIMO's control technology .

History of bipedal robots

Pattern walking from an inverted pendulum



inverted pendulum

It was around 1970 that bipedal robots became the subject of engineering research. At first, it was considered as an extension of the inverted pendulum (en: Inverted pendulum), and research approaches from that direction were actively carried out. An inverted pendulum is a control model of a pendulum placed upside down on a slider (linear motion mechanism). Control the slider so that the pendulum does not fall. This was controlled by PID control so that it would not collapse relatively easily. Successful examples of double inverted pendulum and triple inverted pendulum have also been reported. Since the human foot can be considered as a quadruple inverted pendulum model, it was thought that research into the inverted pendulum model would eventually make it possible to control bipedal locomotion.

A four-fold inverted pendulum model, which resembles a human foot, is given a constraint condition for walking, and the equation of motion is solved to obtain the control amount of each joint. If this movement called a walking pattern is input into an actual robot and moved, the robot should theoretically walk. Since it was not possible to generate a walking pattern in real time due to the ability of computers at that time, the walking pattern was calculated in advance. Therefore, this gait control method was called **pattern gait .**

However, the motors and structural materials at that time were poor, and the difference between theory and reality when actually running this method ended in failure. It was necessary to detect the state of the robot in real time and provide feedback under certain restraint conditions .

ZMP

Since around 1980, various restraint conditions, control methods, and hardware have been studied, and after that, walking based on ZMP became the mainstream. Bipedal walking based on ZMP theory was realized in 1985 by WL-10RD developed by Ichiro Kato and Atsuo Takanishi of Waseda University. Except for the group at Waseda University, ZMP didn't get much attention from the 1970s to the mid-1990s. However, today, almost all bipedal robots with a high degree of perfection, including Honda's ASIMO, use trajectory generation and control using ZMP.

upper body discovery

Despite advances in robot research and advances in actuators and structural materials, robots that walk like humans have been difficult to achieve. As research on human walking and walking experiments on robots have been repeated, it has been recognized again that the action of the upper body is extremely important.

Most of the walking robots at that time imitated a human from the waist down, omitting the upper body. The importance of the upper body has been pointed out since the time of Miomir Vukobratović, the proponent of the ZMP theory, but the motors and speed reducers at that time were poor , so parts other than the leg mechanism were omitted as much as possible. There were many

Position control is the basis for both pattern walking and ZMP, so actuators are also required for the ankles. As a result, the terminal weight becomes large, and the actuator of each joint must be strong and large. Naturally, the

In addition, since the end weight is large, the recoil when the free leg is raised cannot be ignored. When the free leg is lifted and then kicked down, it is in a state similar to that of a ski without weight, and the friction between the pivot leg and the floor surface is reduced. When the friction is reduced, the pivot foot becomes easier to slip. Whether it's pattern walking or ZMP, it's unexpected that the pivot leg moves, and even if it's assumed, there's no sensor that can detect it. If my foot slipped even a little, I would fall over in no time. Moving the heavy legs required constant upper body movements to compensate for dynamic balance.

It should be noted that in today's world where the performance of actuators has improved, walking can be realized without the upper body.

WABOT

Waseda University Faculty of Science and Engineering Ichiro Kato (Robot Researcher)|The research group led by Ichiro Kato is a pioneer in bipedal robot research. He started researching robots in the 1960s, and nicknamed the robot he created WABOT . In 1985, WABOT's 11th machine, WL-11, realized dynamic walking by pattern walking with a humanoid bipedal robot. A slow gait of 1.5 seconds/step. A large potbelly loaded with controllers leans with a thud as it begins to walk. It is unknown whether this was intended from the beginning, but it is presumed that the movement of the upper body counteracted the recoil of the swing leg.

In 1986, this research group developed an upper-body compensating bipedal walking robot WL-12, in which a large weight that resembles the upper body is attached to the waist of the bipedal walking robot in order to more actively utilize the action of the upper body. made. The weights were like dumbbells and could be swung back and forth and left and right. Despite its appearance, the robot achieved a very smooth gait. I was able to go up and down stairs. The results of this research proved that the function of the upper body was extremely important for the walking of bipedal robots.

ASIMO

In 1996, automobile manufacturer Honda announced the humanoid robot P-2. More than anything else, researchers at the time were surprised by the high degree of perfection of the system. First, there were no cables connected to the outside, and autonomous control was possible. With a visual sensor, I was able to judge and walk the route indicated by the mark by myself. Moreover, it was novel in that it had a manipulator that looked like an arm and resembled a human figure. It was known fragmentarily from patent publications that Honda was conducting research on bipedal walking robots, but it was not known that Honda was conducting such full-scale research . Therefore, the announcement of P-2 had a very large impact on both researchers and the general public. Since then, research on walking robots has become popular at once, and various companies have started research on bipedal walking robots. After that, Honda's robot was named ASIMO and commercialized. In December 2005 , the new model of ASIMO achieved a speed of 6 km/h and a jump time of 0.08 seconds. It is the first robot in the world to achieve both walking and running with the same robot (robots that only run have existed since the 1980s).

After ASIMO

In addition to ASIMO, bipedal walking robots have also been researched. In the case of running, impact mitigation technology is important because the impact of landing is greater than that of walking. Also, since both feet are off the ground, posture control during that time requires the same technique as posture control in a weightless state . In order to carry out more advanced activities, it is also necessary to have the ability to appropriately recognize the surrounding situation and predict and judge the future situation. It must recognize steps and obstacles and act in anticipation of them, and must recognize the actions and instructions of humans and other robots. Technologies such as camera-based image recognition and voice recognition are also important technologies for bipedal robots. At present, research on walking control seems to have settled down, and the focus of research on bipedal robots is shifting to research on integrated systems as humanoids .

Mechanism of a bipedal robot

What is a bipedal robot?

A bipedal robot is a robot that has two legs and walks. A robot is **a link mechanism** consisting of **links** and **joints** , and the joints are driven by **actuators such as motors.** A link is a rigid structure, and a joint is a rotary mechanism or linear motion mechanism. A foot (leg) is a serial link mechanism consisting of two or more links connected by a rotating mechanism. There are also robots whose legs are composed of linear motion mechanisms (sliders), but researchers have different definitions as to whether they should be included in bipedal walking robots.

Although researchers differ, the structure of a robot is generally defined as follows. First, the joint corresponding to the ankle is called the first joint, and the second joint corresponding to the knee. The hip joint is the third joint, but the joint that connects to the body is conventionally called the hip joint even in robots. Also, the part that includes the sole is called the first segment, the part that corresponds to the shin is called the second segment, and the part that corresponds to the thigh is called the third segment. The part corresponding to the waist and torso is conventionally called the torso even in robots. There are various variations in the form of the upper body, some with arms, some without a head, and there is no representative one.

what is walking

Main article : Walking

Walking is a type of locomotion method that uses leg movements . The leg that bears the weight is called the pivot leg (also called the pivot leg), and the leg that swings up is called the free leg. Bipedal locomotion is a locomotion method in which the center of gravity is moved in any direction by alternately using two legs as pivot legs.

quiet walking

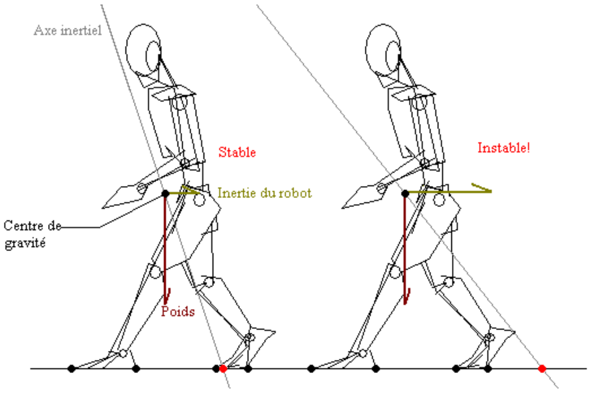
Walking forms include **static walking** and **dynamic walking** . Static walking is a walking method in which the projection point of the center of gravity onto the road surface is positioned on either the left or right sole. The stillness of static walking is the stillness of static stability. Since it is statically stable, it will not tip over no matter where it is stopped, but there are many environmental restrictions, such as the floor must always be flat. Static walking is often used in inexpensive toys.

dynamic walking

Dynamic walking is a concept for static walking. Dynamic walking is a walking method in which the projection point of the center of gravity onto the road surface is off the soles of the feet. Walking performed by humans is also included in this category. The movement of dynamic walking is dynamic stable movement, meaning that it is dynamically stable but statically unstable. It's difficult to control, but it can handle rough environments such as bumpy roads.

Dynamic walking is the main object of research for bipedal robots. In order to realize dynamic walking, it is necessary to accurately collect and judge conditions such as acceleration and reaction force from the floor , and develop technology to respond to and control them.

ZMP



ZMP is a dynamic center of gravity position, and bipedal walking can be realized by giving a constraint condition that ZMP is on the sole. Above is a visual representation of ZMP. The left and right are the same posture, but the left is stable, and the right is unstable because the ZMP is off the sole due to inertial force.

As a method to realize dynamic walking, the walking control method based on ZMP has become mainstream. In control engineering terms, a norm is a combination of boundary conditions and constraint conditions .

In 1972, Miomir Vukobratović et al. of the Mihailo Pupin Institute in Yugoslavia (now the Republic of Serbia) developed a trajectory generation method and a control method for a bipedal robot based on a walking norm called **Zero Moment Point** (ZMP). Announced. ZMP is the center of pressure of the ground reaction force and can be calculated from the motion of the robot and the equation of motion. Bukobratovic et al. preset the time trajectory of ZMP that moves within a support polygon, and obtained the corresponding walking motion by iterative convergence calculation. By using ZMP, it is possible to design a walking motion that strictly considers all the influences of the swing leg and the mass of the upper body.

ZMP is a law of motion such that the projection point of the dynamic center of gravity is located in the stable area (≒the sole of the foot). Walking by ZMP is classified as dynamic walking because it is "dynamic" but different from static walking. However, even though it is the same dynamic walking, ZMP walking is not the same as human or animal walking. Walking by ZMP is a law of motion that is unrelated to the law of conservation of energy, so it consumes a lot of energy. Living organisms such as humans walk long distances with less energy, but ZMP cannot explain it.

Passive walking (passive walking)

Passive walking (passive walking) is known as a rattling toy that walks on a slope without any power [12] [[13] . in a state . Neither statically nor kinetically, there is no projection point of the center of gravity on the sole, and it can be defined as complete dynamic walking. It can be classified as a trot in terms of gait. If bipedal walking is considered to be vibration, it can be explained that humans and penguins can walk long distances with a small amount of calories. Studies on passive walking include the following [13] . For example, McGeer (McGeer, 1990) theoretically demonstrated that walking on a downhill slope could be a stable limit cycle in a simplified model of unpowered bipedal locomotion, and built a robot with passive locomotion. [13]] . In addition, Nobuhisa Yamazaki

(1984) created a mechanical model of the human body, and showed that when the model was hung from the head and vibrated, movements similar to walking patterns were created[14] . In such passive walking, the pendulum characteristic of the musculoskeletal system plays an important role, and it is thought that the characteristic of spring elasticity also contributes to motion generation [15] .

gait

As a physical education classification of walking, there is a classification by gait (sometimes written as gait or gait). Bipedal gaits include walk (running foot, knee-foot), trot (fast walk, high-foot), and gallop. If you just say walking, you can think of it as a trot.

A trot is a walking style in which the pivot foot alternates and one foot is always on the ground, without a jumping period. The pivot legs are exchanged instantaneously, and the period of weight bearing on both is short or negligible. In the case of trot walking, the seemingly complicated movement of walking can be regarded as a rotational movement about the ground contact point of the pivot foot , and the equation of motion can be established relatively easily. For this reason, walking control based on trot is usually applied to bipedal robots.

If walking is rotational motion, centrifugal force should be generated. Centrifugal force at this time $F$is expressed by the following formula. $v$is the moving speed of the center of gravity (=walking speed), $r$is the height of the center of gravity, $m$is the mass.

$$F = \frac{mv^2}{r}$$

Replacing F with mg leads to the following equation: $g$is the gravitational acceleration .

$$v = \sqrt{gr}$$

This is a formula that expresses the limit speed of walking, and means that if you walk faster than this, your legs will naturally leave the floor due to centrifugal force, and you will move to running. Assuming that the height of the center of gravity of a human being is 1 m, the limit speed for walking is 11.2 km/h (by the way, the world record for race walking is 13.6 km/h (50 km). This is a theory because twisting of the waist and strokes of the soles of the feet are added. higher than the numbers above). Even if the walking robot does not run, when the walking speed increases, the centrifugal force makes the pivot leg more likely to slip, making the walking robot more likely to topple over.

In trot walking, the horizontal momentum is theoretically 100% transferred to the next step. The vertical momentum is lost due to collision with the floor, but in the case of humans, the Achilles tendon stores the potential energy of the center of gravity, and it is thought that the body is kicked up when the pivot foot is changed and transmitted to the next step. ing.

A walk is a gait with a period of weight bearing on both legs. In this gait, when both feet are on the ground, the direction of the velocity vector of the center of gravity is constrained in one direction. Therefore, in addition to the vertical momentum, the horizontal momentum is lost for each step (the trajectory of the center of gravity becomes zigzag), so the energy cost is significantly worsened. Therefore, it is thought to be a form of locomotion that is rarely performed by humans or birds. In addition, since the motion mode differs between two-legged and single-legged robots, the control becomes complicated, so it is not often used even in bipedal robots.

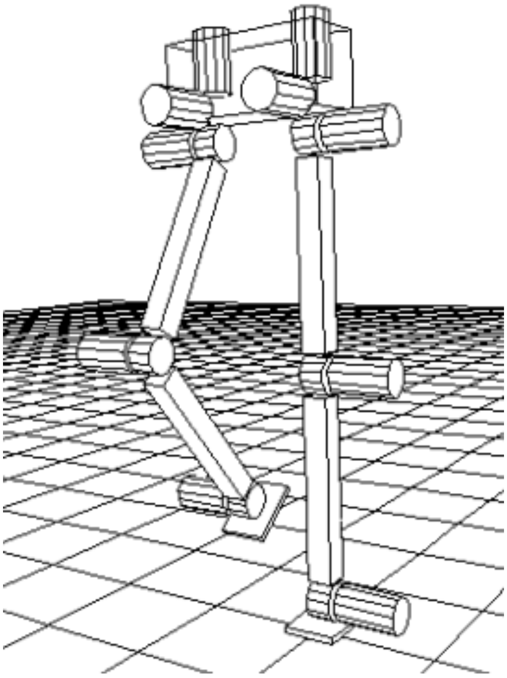
A gallop is a gait with a jumping phase, so-called running. Leaping period is the period when both legs are not touching the ground.

The definition of walking here is an example of a definition in engineering. In addition, there are differences among researchers in the classification and naming of gaits.

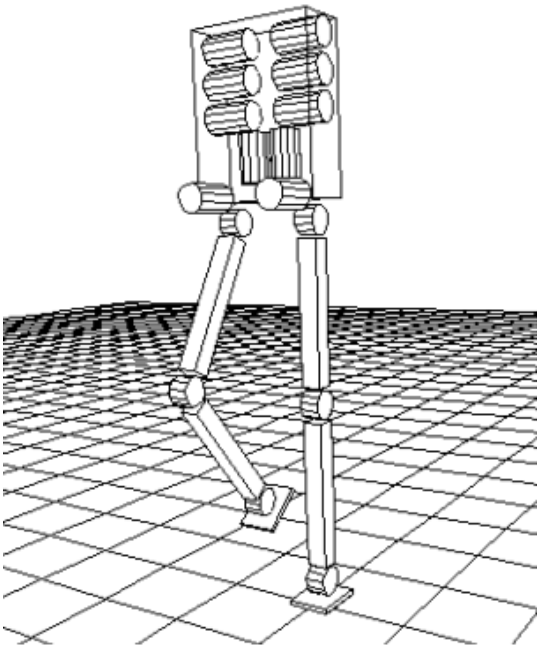
control model

In control engineering, when considering a controlled object, the controlled object is abstracted so that it can be easily expressed in mathematical formulas, and the abstracted controlled object is called a control model, or simply **a** model **.** The closer the control model is to the real thing, the more accurate control becomes possible. Biped robots use a control model that abstracts humans and birds.

human model



A control model of a humanoid bipedal walking robot. The cylindrical shape represents the placement of the motors. A bodyless type that was often seen in the early stages of research on bipedal walking robots. It was difficult to control walking due to the large impact of leg swing.



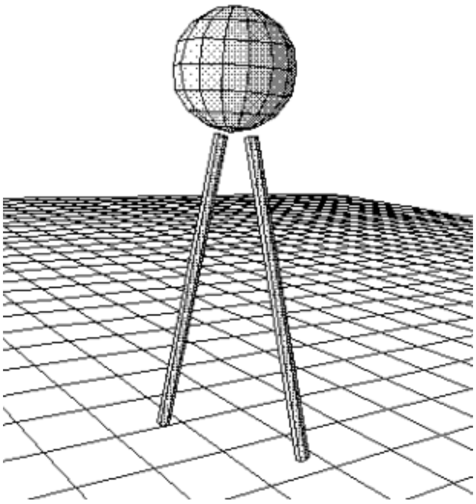
A control model of a bipedal humanoid robot with a torso. Most of the current humanoid bipedal walking robots are of this type. However, in the figure, the motors that drive the legs are placed in the body, but there are no robots that actually have motors placed like this. The fuselage contains a battery and a control device.

Many bipedal robots walk by controlling the position and speed of the center of gravity by ZMP, but in this case ankle torque is necessary. When the end weight is increased by the ankle actuator, the stable area becomes narrower, and the center of gravity fluctuates significantly during walking, making control extremely difficult. Humanoid robots can cancel or mitigate center-of-gravity fluctuations by moving the upper body.

The torso resembles a human, standing vertically. As a result, the center of gravity of the torso is positioned well above the hip joints and has an eccentric moment . Therefore, when the robot starts walking, the recoil is transmitted to the body as a moment force. Since it is necessary to transmit this moment force to the floor surface and cancel it, each leg joint requires a fairly strong actuator and a large sole. Humanoid models require ankle torque for dynamic balance. It is for the same reason that human legs are thicker and stronger than those of birds. As such, humanoid model robots tend to be robust. Large robots require expensive servo motors and harmonic drives, and are expensive to manufacture.

Even in upright bipedal walking in organisms , the center of gravity of the body does not match the position of the hip joint, and a huge moment (rotational force) is generated from the body. The muscles have to hold this in place, so you need big legs and extra energy to move them. It is believed that the lack of upright bipedal locomotion in nature is due to poor energy efficiency.

massless leg model



Massless leg model. A control model for an ideal bipedal robot with no mass on its legs.

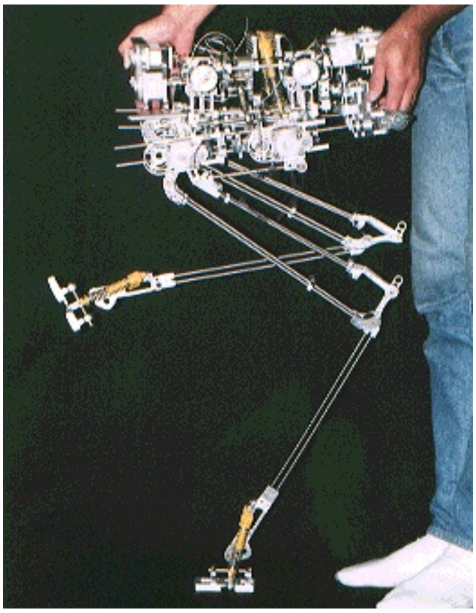
The most ideal model of a walking robot is a massless leg model, which is a theoretical control model. The legs have zero mass and are perfectly rigid. Assume all mass is in the fuselage. The position of the center of gravity of the torso and the position of the hip joints are exactly the same. Therefore, the position of the center of gravity of the whole body also coincides with the hip joint.

With a massless leg model, the center of gravity does not change due to the movement of the leg. Furthermore, since the hip joint and the center of gravity of the trunk are aligned, no moment force is generated, no torque is required to cancel it, and no ankle torque is required. The equation of motion is simple because it is only necessary to consider the force on the floor, reaction, and the position of the center of gravity, and the number of actuators is minimal, so control is easy. Around 1980, the massless leg model was actively studied for theorization of walking phenomena.

The massless leg model is the easiest model to realize walking, but of course it is impossible to actually produce it. However, there are many examples of research on robots that are close to that. In Japan, **bipedal robots** called stilt robots have been studied since around 1980. The stilt robot has an actuator at the waist that moves the legs. There are many types that expand and contract to make the legs lighter. In principle, there is no need for a part corresponding to a human foot (from the ankle down), but it has an ankle equipped only with a potentiometer to detect tilt. This type was the earliest to realize dynamic walking in robots because the mechanism is simple, easy to manufacture, and easy to control. In 1982, Isao Shimoyama et al. of the University of Tokyo published a paper on dynamic walking by a stilt-type robot.

In Europe and the United States, it is called **a hopping robot** or **hopping machine , and research is more advanced than in Japan.** Hopping machines that can be said to be massless leg models are those with one or two legs, and have been running since the 1980s. However, the hopping robot cannot walk because it will fall down if it does not jump.

bird model



A bird-type bipedal walking robot. A motor is placed in the torso, and suspension is installed in the ankle and hip joints. There are no actuators in the ankles.

It is a bipedal walking model shaped like a bird. It has a long torso and legs with a second joint that bends forward. In some cases, the 4th section is set between the body and the 3rd section. Biological birds have a fourth section.

There are hip joints on both sides of the body, and the position of the center of gravity coincides with the position of the hip joints on the sagittal plane. Since the center of gravity of the body matches the hip joint, there is no eccentric moment in the body. Therefore, since there is no need to transmit the moment force to the floor surface, no ankle torque is required. Therefore, in a bird-type bipedal walking robot, the ankle actuator may be omitted or may be small. Since the terminal weight can be reduced, the actuators for the second joint and the hip joint can also be made smaller. Therefore, it is possible to reduce the weight of the entire leg. Since the legs are light, the position of the center of gravity of the whole body almost matches the position of the hip joint, and the power to kick the ground can be transmitted directly to the center of gravity. For this reason, the tri-type model has good maneuverability, can run at high speed, and is said to have a low energy cost. [16]

A bird-type bipedal walking robot was produced around 1990 at the National Institute of Advanced Industrial Science and Technology and Shinshu University . In 2004, the Toyota i-foot was produced. Aiming at demonstrating the walking theory by ZMP, the robot of the Institute of Advanced Industrial Science and Technology adopted the theoretically most rational bird type. Shinshu University's robot is the first walking robot equipped with a suspension . By attaching springs and dampers to the ankle and hip joints, we aimed to demonstrate a unique gait theory that can be handled in a modeless manner from walking to running.

Bird-type locomotion is much more common than upright bipedal locomotion in the living world. This is believed to be due to their good mobility and high energy efficiency. In fact, ratites such as ostriches are said to be able to run for long periods of time at speeds of 80 km/h or more. This is slower than the cheetah , but the cheetah's top speed lasts only a few seconds. Ostriches are said to be superior at long distances.

dinosaur model

A dinosaur model is a derivative of the bird model. The dinosaur-type model is a bird-type model with a body that is longer back and forth. The part corresponding to the tail actively cancels out the eccentric moment. It is thought to be more suitable for high-speed driving than the bird-type model, but the range of indoor applications is considered to be narrow because the tail and neck get in the way when turning. These robots are mainly being researched in the United States. Recent research on dinosaur locomotion has been remarkable, and the results of research on walking robots have also contributed in no small way.

Dinosaur models are able to maintain balance with their long torso, so even **static** walking can be quite dynamic. For static walking, there is no need to deal with equations of motion, and it is easy to incorporate an impact interference mechanism. The required level of control is low, and safety is high because it does not topple over even when walking is stopped . At present, a large dinosaur-type walking robot is being developed at the National Institute of Advanced Industrial Science and Technology [17] .

Gait generation

In this article, the context is divided into gait control using gait patterns (gait control that controls the position of the center of gravity) and gait control that does not use gait patterns (gait control that does not control the position of the center of gravity). In recent years, research on passive walking is progressing, and categorization with conventional walking control methods is being formed, but this is not necessarily a formal classification method.

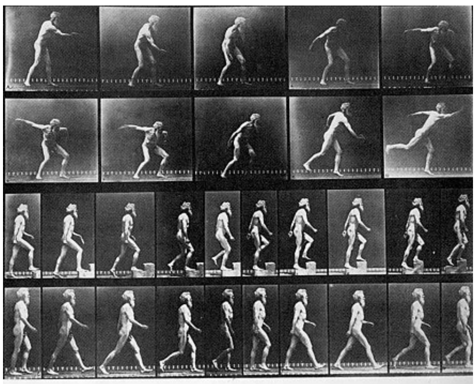
Gait control by walking pattern

The current mainstream method is to control walking by controlling the position of the center of gravity. Most walking robots adopt this method because it can be developed based on position control that is technically sophisticated. Walking control using ZMP also realizes walking by controlling the position of the center of gravity.

The amount of joint angle control when a robot walks is called **a walking pattern .** Different researchers use various terms such as walking trajectory and walking control amount. In the past, due to the lack of computing power, walking patterns were generated in advance and then reproduced by robots in an attempt to achieve walking. This method is unsuccessful due to the gradual deviation between the calculated values and the actual behavior of the robot. With the development of computers, it became possible to generate walking patterns by feedback of behavior in real time, and walking became possible. For the walking pattern, the motion equation of the control model is established, the constraint conditions for the walking method are entered, and the motion equation is solved to obtain the control amount.

The equation of motion is a formula that expresses the relationship between how much force is applied to a joint, how the posture of the body changes, and what happens to the position of the center of gravity and the moment force. The equation of motion can be established by considering each interaction for each link, but it is not easy to establish the equation of motion when there are many link mechanisms such as a walking robot. Normally, the equation of motion is created using the Euler-Lagrange equation of motion.

This equation is derived from the basic law of physics that the change in potential energy is equal to the change in kinetic energy unless an external force is applied. Since the motion of the robot is three-dimensional, the formula consists of matrices and vectors.



By Eadweard Muybridge. In the pattern walking, the movement obtained from such continuous photographs was used as a constraint condition.

Since the walking robot has many degrees of freedom, the walking pattern cannot be obtained simply by solving the equation of motion. Some constraint must be put in. The constraints are the walking patterns and ZMP of humans and birds. In ZMP, a relational expression is set up so that the dynamic center of gravity position is above the sole, and it is combined with the above equation of motion to solve the simultaneous equations. When you solve the equation, the determinant expresses which joint will move where the ZMP will be, or how much you need to move which joint to move the ZMP to a certain position.

The walking pattern is one pattern from when the free leg leaves the floor until it reaches the floor again. Theoretically, the robot walks when the control amount for each actuator for one pattern is generated and input to the robot for each step. In today's high-performance computers, it is possible to calculate walking patterns in real time. Attempts have been made to prepare a standard walking pattern and apply a subtle bias to it so that it can respond to changes in the environment to some extent.

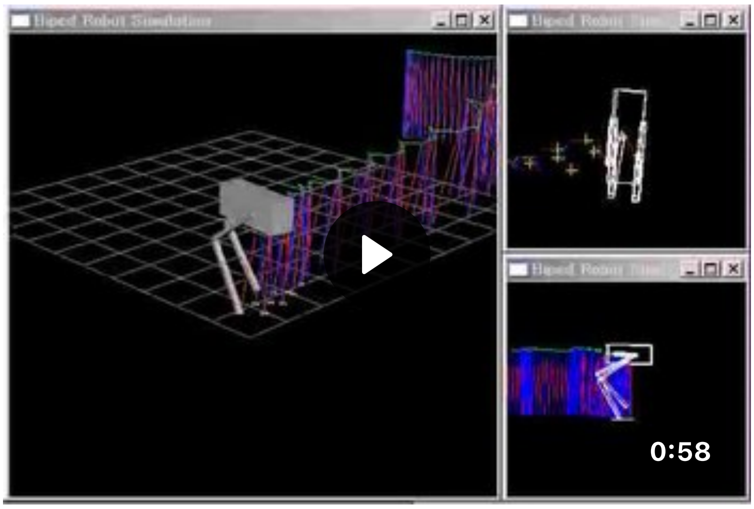
In the walking control method using walking patterns, it is necessary to solve the equation of motion, but if there is an elastic body (so-called spring system) in the robot , it becomes impossible to solve the Euler-Lagrange equation of motion. Therefore, currently available walking robots are designed to have no spring system as much as possible. This is the reason why shock absorbing mechanisms such as suspensions are not used in walking robots, and this is one of the factors that make it difficult for walking robots to run.

Gait control without gait pattern

Walking using a walking pattern is performed by actively controlling the position of the center of gravity, but there is also a walking control method that does not control the position of the center of gravity. Different researchers call it algorithmic walking, walking control by inverted pendulum mode, event walking, and walking control based on rhythmic motion . In addition, it has a high affinity with passive walking in that the position of the center of gravity changes passively .

There are examples of application in bipedal walking robots that are close to massless leg models, such as stilt type bipedal robots and bird type bipedal walking robots. The advantages of walking control using algorithms are that it is not necessary to solve the equation of motion, so it is possible to attach a shock absorbing mechanism, that manufacturing costs can be kept down because the machining accuracy is low, and that failures that occur during operation (such as falls) distortion of the frame, malfunction of the drive system), and since it can handle load fluctuations, it can handle the transportation of loads and the action of external forces. In addition, since the motion conforming to the law of conservation of energy becomes possible, the energy efficiency can be remarkably improved as compared with the walking control using the walking pattern.

For example, in the motion simulation video of bipedal walking on the left, walking is generated with very simple mathematical formulas, and direction changes and speed control are performed by arbitrarily shifting the free leg landing position and kick force. Since walking can be controlled by a single vector, it is possible to control the robot with the control stick and accelerator/brake [18] .



Algorithmic biped walking example [19]

Biped robot hardware

The hardware of a bipedal walking robot consists of a frame, actuators, a control system, and a power supply. In the past, the control system and power supply were often placed externally, but the miniaturization of the battery and control equipment has made it possible to install them in the robot itself. The components of bipedal walking robots are not much different from industrial robots, but unlike industrial robots, walking robots are moving objects like automobiles , and their design is somewhat similar to the concept of automobiles and motorcycles . That is, the lighter the weight and the higher the output, the better, and the smaller the unsprung weight (which corresponds to the mass of the leg in a walking robot) and the terminal weight, the better. It is also similar in that the position of the center of gravity has a large effect on motion characteristics.

Biped robots are currently under research and development, and there is no standard structure, but I will briefly explain the current trends and their background.

framework

The framework of a bipedal walking robot corresponds to **the links (nodes) of the control model.** When performing walking control based on ZMP, which is currently the mainstream, since position control is the base, the link of the control model is assumed to be a completely rigid body , so high rigidity is required for the frame of the robot that is actually manufactured. . Naturally, it is required to be strong enough not to be distorted even if it is overturned. Also, high accuracy is required, and if the machining accuracy is low, control may become difficult. In the past, aluminum was sometimes used to reduce weight, but in recent years, steel has been used more often with emphasis on rigidity and workability. By the way, industrial robots also use cast steel and steel plates with emphasis on rigidity. Composite materials such as carbon fiber reinforced plastics are superior in terms of rigidity , but they are not often used because they are extremely difficult to process.

An exoskeleton structure is often used to reduce weight , but an endoskeleton structure is sometimes adopted because it is easy to distort when falling. The endoskeleton structure also has the advantage of being easy to outfit and easy to repair.

power conversion mechanism

Servomotors are used as actuators for bipedal robots . Hydraulic pressure , pneumatic pressure , artificial muscle , etc. are sometimes used, but there are few examples. Since the servo motor rotates at high speed, it is necessary to reduce the rotation speed with a speed reducer and increase the torque. Gears are used for speed reducers , but planetary gears or harmonic drives are used for bipedal robots . A harmonic drive is a speed reducer that uses a differential between an ellipse and a perfect circle, and is used in many walking robots due to its small size, light weight, and high efficiency. However, it is very expensive.

A servo amplifier is required to drive the servo motor. Robot servo amplifiers, including industrial robots, usually use PWM drivers to improve robustness . PWM is a method that supplies the maximum current of the motor in + and - pulses, and always uses the motor at maximum load. Servo amplifiers are power devices, and general-purpose products are large and heavy due to their heat capacity. In order to install it on a robot, it is necessary to request a custom-made product or make one yourself.

robot competition

Small (about 10 to 30 cm) bipedal robots have been actively researched by individuals and small groups, especially in Japan. This is largely due to robot competitions such as RoboCup and ROBO-ONE . From February 24 to 26, 2011, the world's first full marathon event for bipedal walking robots was held, and the top finisher was 54 hours, 57 minutes and 50 seconds [20] .

Main bipedal robots

- A bipedal walking robot developed by Valkyrie (NASA , USA). [21] [22] [23] [24] [25] [26]
- WABOT-1 (Waseda University : The world's first electrically controlled bipedal walking robot)
- ASIMO (Honda Motor Co., Ltd.): Developed with a view to practical use [27]
- E2-DR (Honda Motor Co., Ltd.): A disaster relief robot (prototype) announced at IROS 2017, an exhibition related to the robot industry held in September 2017 in Vancouver, Canada [28] .
- RHP (Robust Humanoid Platform) (Jointly developed by Kawasaki Heavy Industries, University of Tokyo Information Systems Engineering Laboratory (JSK) , etc.) (https://translate.google.com/website?sl=auto&tl=en&hl=en&client=webapp&u=http://www.jsk.t.u-tokyo.ac.jp/index-j.html) A prototype robot (version 4) presented at the exhibition "iREX 2017" [29] .
- Kaleido (Jointly developed by Kawasaki Heavy Industries , Information Systems Engineering Laboratory (https://translate.google.com/website?sl=auto&tl=en&hl=en&client=webapp&u=http://www.jsk.t.u-tokyo.ac.jp/index-j.html) (JSK), University of Tokyo, etc.): International Robot Exhibition held at Tokyo Big Sight from October 17th to October 21st WRS 2018" prototype robot (version 5) [30] .
- HRP-2 (Joint development with Kawada Industries , National Institute of Advanced Industrial Science and Technology , etc.) [31]
- HRP-2 Kai (Jointly developed by Kawada Industries , the National Institute of Advanced Industrial Science and Technology, etc.): DARPA Robotics Challenge June 2015 Finals (out of 23 teams) 10th place [32]
- JAXON (Developed by the University of Tokyo): DARPA Robotics Challenge June 2015 Finals (out of 23 teams) 11th place [33] [34]
- HRP-3 (Jointly developed by Kawada Industries , National Institute of Advanced Industrial Science and Technology , etc.) [35]
- HRP-4 (Joint development with Kawada Industries , National Institute of Advanced Industrial Science and Technology , etc.) [36]
- HRP-5P (Jointly developed by Kawada Technologies , Honda Motor Co. , Ltd. , National Institute of Advanced Industrial Science and Technology, etc.) [37] [38]

- KHR-1 (Kondo Kagaku): Marketed for enthusiasts
- i-SOBOT (Takara Tomy): Marketed for home use. It was inexpensive and had 17 degrees of freedom .
- QRIO (Sony): Although the prototype was relatively complete, it was not released.
- Toyota i-foot (Toyota Motor Corporation): A ride-on bipedal robot that was unveiled at the Aichi Expo .
- T-HR3 (Toyota Motor Corporation): Exhibited at the 2017 International Robot Exhibition held at Tokyo Big Sight from November 29 to December 2, 2017 [39] [40] [41] .
- LAND WALKER (Sakakibara Machinery): Ride-on type, but not strictly bipedal.
- HUBO + (DRC-HUBO) (Republic of Korea · Korea Advanced Institute of Science and Technology (KAIST)): DARPA Robotics Challenge 2015 June main competition (out of 23 teams) 1st place [42] .
- WALK-MAN (Whole-body Adaptive Locomotion and Manipulation) (Italian Republic / Italy Institute of Technology (IIT)): DARPA Robotics Challenge June 2015 main round (out of 23 teams) 17th place . [43] [44] [45] [46] [47] [48]
- iCub Republic : Italian Institute of Technology (IIT) [49] is a child-type bipedal robot that is being researched and developed mainly[50] . The design is open source and can be customized in any way [51] .
- REEM-C (Barcelona , Spain):A bipedal walking robot with a height of 165 cm, a weight of 80 kg, and a total of 44 degrees of freedom developed by PAL Robotics [52] (announced in July 2013). [53] [54] [55]
- TALOS (Barcelona , Spain): A bipedal walking robot with a height of 175 cm, a weight of 95 kg, and a total of 32 degrees of freedom, which is being researched and developed mainly by PAL Robotics. [56] [57] [58]
- TORO (Torque Controlled Humanoid Robot) (Germany / German Aerospace Center): A bipedal walking robot developed for the purpose of collaborating with astronauts in outer space (announced March 2013). Height 174 cm, weight 76.4 kg. [59] [60] [61] [62] [63]
- FEDOR (Final Experimental Demonstration Object Research) (Russian Federation): A bipedal walking robot developed by Android Technics [64] and the Foundation for Advanced Research (published in October 2016) [65] [66] .

  On July 23, 2019, the new bipedal walking robot "Skybot F-850" [67], which succeeded in reducing size and weight by adding a voice assistant function, was released on the Twitter page [68] [69] . [70] .
- DARwIn-OP [71]]
- Precursor (People's Republic of China , Changsha City , National University of Defense Science and Technology)
- Walker (Headquarters: Shenzhen City , Guangdong Province , People's Republic of China / US Headquarters: Los Angeles , California , USA , UBTECH [72]): The official name is "Intelligent Humanoid Service Robot" [73] . A bipedal walking robot with a height of 145 cm, a weight of 77 kg, and a total of 36 degrees of freedom [74] . Exhibited at "CES 2019" held in Las Vegas, USA from January 8, 2019 to January 11, 2019 [75] [76] [77] .
- PETMAN (Waltham , Middlesex County , Massachusetts , USA , Boston Dynamics) [78]
- Atlas (Waltham , Middlesex County , Massachusetts , USA , Boston Dynamics) [79]
- Digit (Oregon State University, Oregon State University , USA , Agility robotics [80]): A new bipedal walking robot scheduled to start mass production and delivery in 2020 (announced February 26, 2019) [81] [82] .
- Gynoid
- Nao (Aldebaran Robotics , France)
- Romeo (France Aldebaran Robotics, fr:Cap Digital) [83]
- ASRA C1 (Asratec)

- PALRO (Fujisoft)
- S-1 (SCHAFT): DARPA Robotics Challenge December 2013 qualifying leader (missed June 2015 final)
- Sota (robot) (Joint development with Vstone , Nippon Telegraph and Telephone , NTT Data , etc.)
- Robozero (Deagostini Japan)
- Robi (Deagostini Japan)
- PLEN (PLEN Project)
- RoBoHoN (Sharp)
- Tesla Bot "

footnote

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