Design of Statically Stable Walking Robot: A Review

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The superior mobility characteristics of legged animals compared to those of wheeled or tracked vehicles for off-road locomotion motivated the development of artificial walking machines. The sustained worldwide efforts for the last few decades resulted in a large number of legged robots with different levels of sophistication. Here, various design approaches made so far to realize artificial legged locomotion are discussed. Mainly, different vehicle configurations as well as leg mechanisms which are already explored by researchers are reviewed in brief. The author hopes that this will serve as a brief account of previous research efforts and help future walking robot designers to develop more sophisticated machines.

1. INTRODUCTION

Manmade means of terrestrial locomotion are based on the wheel, while legged animals in nature use legs for locomotion. It is natural to think that animals have been forced to adopt an inferior legged locomotion scheme due to the inability of nature to create a continuously rotating joint. However, the advantage of rotating systems for transportation is primarily energetic and only in a limited range of circumstances.[1] The maneuverability of wheeled vehicles becomes severely restricted in cluttered terrain. The scarcity of rotating systems in nature appears to be more due to the limited utility of such systems in natural terrain than due to the constraints intrinsic to biological systems (physiological problems of nutrient supply).

Over recent years, growing interest for developing legged robots and combination of innovative engineering with scientific observations on legged animals[2] resulted in a number of artificial walking systems. Although many projects are found to be more or less similar, the experience gained through all these studies enriched the area of research on artificial legged machines significantly. However, there is no consolidated report briefing the merits of each of these approaches. The purpose of this work is to summarize the contributions made in the design of artificial legged systems. This information can be

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useful for designing improved walking robots. Here, the scope is restricted to statically stable walkers only.

The article is organized in the following order. In the next section, the significance of number of legs on walking robot performance is discussed. In Section 3, the focus is on different machine configurations. Various leg designs used are addressed in Section 4. Section 5 outlines some of the unexplored areas. Finally, recent trends in the research on walking robot development are given in Section 6.

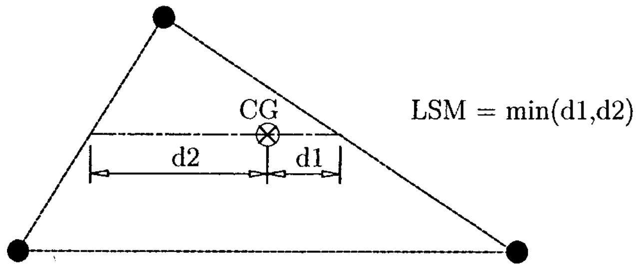

Figure 1. Longitudinal stability margin (d1: forward stability margin, and d2: backward stability margin).

2. NUMBER OF LEGS

Statically stable walking requires at least four legs so that three legs can maintain stability and the remaining one can be used for exchanging support. Similar to biological systems, symmetry has an important role in balancing as well as in the design of the control architecture of artificial systems and it requires that the number of legs be even. There are some advantages when the number of legs increases. Most significant among these are the speed of locomotion and the stability. These are explained in the following.

Before starting the discussion, let us define some terminologies used. Since the leg is not a continuous locomotion element like a wheel, it must alternately support the robot and move forward with respect to the body for next foothold to begin another locomotion cycle. The *transfer phase* (or swing) of a leg is the period in which the leg is in the air. The *support phase* (or stance) of a leg is the period in which the leg is on the ground. The *support pattern* of a legged system is a two-dimensional point set in a horizontal plane consisting of the convex hull of the vertical projection of all foot points in support phase. A gait of any legged system is the *corporate motion of the legs*, coordinated with the motion of the body in order to move it from one place to another in such a manner that stability is always maintained. The condition for static stability of the system is that the vertical projection of its center of gravity falls inside the support pattern. Stability for any machine state can be quantified by the parameter *longitudinal stability margin*, which is the shortest longitudinal distance from the vertical projection of the center of gravity to the boundaries of the support pattern in the horizontal plane (Figure 1). Leg stroke (R) is the distance through which the foot is translated relative to the body during the support phase (Figure 2). The *duty factor* is defined as the fraction of the cycle time each foot is on the ground (assumed to be the same for all feet).

The major limit on speed in most legged locomotion systems is the time required to return the leg through the air to its starting position. Let τ be the return time of the foot. Then, according to the definition of duty factor (β),

$$\tau = (1.0 - \beta)T,$$

where T is the cycle time. The vehicle speed V can be written as

$$V = \frac{R}{T\beta}.$$

Here, R is leg stroke. Substituting T from the two above equations, we get

$$\tau = \frac{R}{V}\left(\frac{1.0 - \beta}{\beta}\right).$$

Now let us consider a possible return path trajectory. A rectangular foot trajectory with horizontal sides equal to stroke and vertical sides equal to the foot clearance (h' = maximum distance between foot and

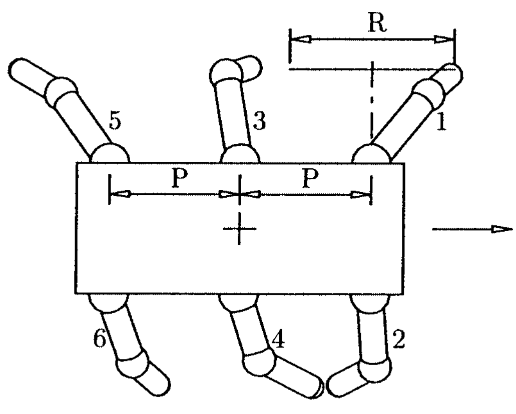

Figure 2. Leg stroke in a typical walking robot.

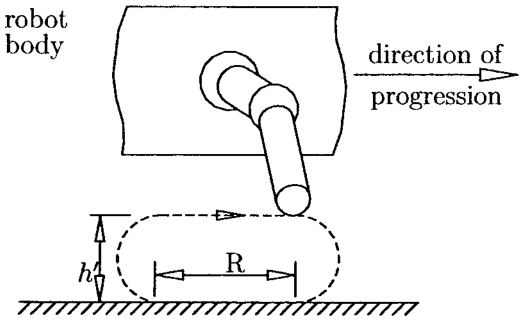

Figure 3. A simple foot trajectory.

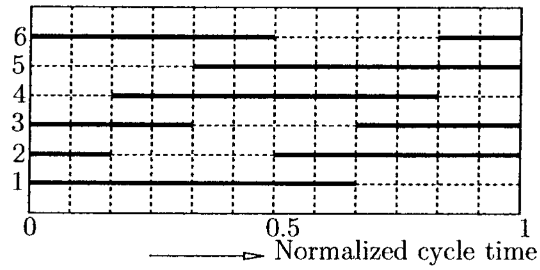

Figure 5. Gait diagram of wave gait ($\beta = \frac{2}{3}$).

ground during return stroke of a leg) is simple. To avoid the discontinuities at the corners, let us join the horizontal sides by semi-circles of radius equal to half of the foot clearance as shown in Figure 3. Total length of the return path is

$$R' = R + \pi h'.$$

Let the limiting return speed of foot be $V'_{\max}$. The foot has to accelerate from vehicle speed to this maximum foot speed during first part of the return stroke and to decelerate later again to the vehicle speed. For simplicity, if it is assumed that $V'_{\max}$ remains uniform throughout the return path, the maximum walking speed can be expressed as

$$V_{\max} = \frac{R}{R + \pi h'} \frac{1.0 - \beta}{\beta} V'_{\max}. \tag{1}$$

Actually, the average foot return speed will be less than $V'_{\max}$ and, hence, the maximum walking speed $V_{\max}$ will be even lower.

Figure 4 illustrates the benefit of having more legs in terms of stability and speed of locomotion. Four-, six-, and eight-legged systems are compared. The minimum duty factor for a four-legged statically stable system is $\frac{3}{4}(=0.75)$. For six- and eight-legged systems minimum duty factors are $\frac{3}{6}(=0.5)$ and $\frac{3}{8}$ $(=0.375)$, respectively. The maximum duty factor is considered close to unity. For any given system, the minimum longitudinal stability margin (LSM) is calculated for different duty factors. For simplicity, regular wave gait is considered. Figure 5 illustrates one such gait corresponding to the six-legged robot shown in Figure 2. It shows support by each foot against time. The beginning and end of a darkened line correspond respectively to the placing and lifting of the corresponding foot. Leg stroke and pitch are assumed to be equal and the LSM is normalized to the leg stroke. Similarly, the maximum robot speeds corresponding to each value of duty factors are calculated using Eq. (1). As observed in Figure 4, for a machine with a given number of legs and maximum foot return speed, as the vehicle speed increases, the duty factor for each foot reduces, causing the machine to be supported by a smaller number of legs. As a result, LSM decreases. In other words, for a machine with more legs, with vehicle speed and maximum foot return speed remaining unchanged, more legs support the machine at any instant, resulting in higher stability margin.

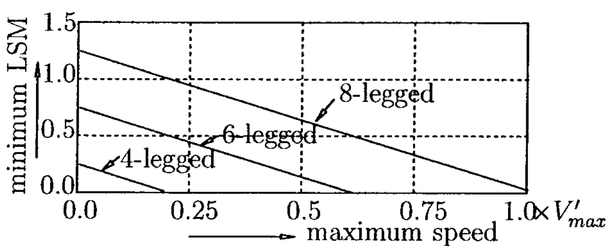

Figure 4. Maximum vehicle speed, minimum longitudinal stability margin, and number of legs.

Another important benefit is that with more than four legs, ideally it is possible to recover from accidental situations when some legs are disabled. Also, the fraction of total vehicle weight each leg has to support decreases with the increase in number of legs.

However, the complexity in driving mechanism, coordination, and control increases with the increase in number of legs. Most of the early machines were hexapods because six legs allow walking with a stable alternating tripod gait in which, at any instant, the machine can be supported by three legs (the middle leg of one side along with front and rear of the other). As mentioned earlier, statically stable walking requires the machine should have minimum four legs and since the isolation of the robot body from terrain irregularities requires at least three degrees of freedom in each leg, 12 independently controllable degrees of freedom are the minimum requirement for any statically stable terrain adaptive walker. For six- and eight-legged systems, these are 18 and 24, respectively. Prior to the advent of compact and powerful computers, automatic coordination of such a large number of motions by means of an on-board controller was impossible. Even now, when far superior control and computational schemes are available, except for the robot lobster,[3] the number of legs for terrain adaptive walking robots (i.e., each leg with three or more degrees of freedom) is restricted to within six.

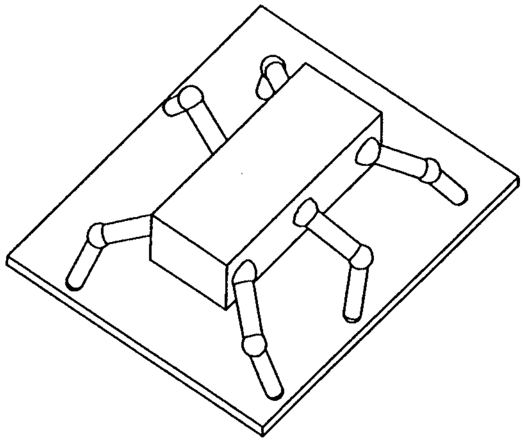

Figure 6. Typical walking robot configuration.

3. MACHINE CONFIGURATION

Although the locomotion system in legged animals does not differ much, engineers have many alternatives and previous efforts resulted in a number of legged robots with wide variation in shape, size and sophistication.[4] Based on the machine configurations, walking robots can be broadly classified into four groups: simple, hybrid, twin framed, and articulated body. While designing an artificial walking system, it is probably easier to start with a number of legs connected to a rigid body. Walking robot designers concentrated on this simple machine configuration for many years. Later, to reduce the high load bearing capacity requirement of legs, wheels were added. In such hybrid systems, legs were used mainly for traction. Since wheels restrict the performance during rough terrain locomotion, some hybrid systems were built with provision for switching between wheeled mode and legged mode depending on the terrain condition.

The efforts to reduce the number of actuators to be controlled resulted in twin-framed walking robots. In this type of walking robot, a number of legs with reduced degrees of freedom were mounted to each frame, providing stable support for the rest of the machine. The walking motion was realized by alternatively moving legs on one frame forward while the legs on the other frame supported the machine. Although the grouping of legs in twin-framed walking robots simplified control, the terrain adaptability was reduced drastically. In nature, the superior terrain adaptability of legged animals is partly due to the articulated design of their body. Earlier, due to the state of development of control systems and computers, it was not feasible to realize such designs. Recently, a few walking robots with articulated bodies were developed. Of course, the order of body articulation is less and not comparable with that of biological systems.

In the following, the walking machines under each of these categories are discussed.

3.1. Simple

The majority of walking robot projects are of this type, with an even number of identical legs symmetrically connected to the sides of a central body (Figure 6). In most cases, the shape of the body is rectangular.

In as early as 1940, A. C. Hutchinson and F. S. Smith[5] in Britain built a model having four legs each with two joints. Ralph Mosher of General Electric's General Engineering Laboratory built a four-legged walking truck[6,5] in the mid 1960s, with three degrees of freedom per leg. These vehicles were extremely demanding on their drivers. For both of these machines, each of the driver's limbs was connected to a handle or pedal that controlled one of the four legs. In the computer era, the major aim was to develop a walking machine capable of terrain adaptation. In 1966, Robert McGhee and A. A. Frank at the University of Southern California built a four-legged machine Phony Pony[6] with two degrees of freedom per leg. Joint coordination was performed by an electronic sequencer made of flip-flops. This was the first legged vehicle to walk under full computer control.

In 1976, Taguchi *et al.*[7] in Japan built a four-legged walking machine using finite state controlled binary actuators. Okhotsimski and his colleagues at Moscow Physico-Technical Institute developed a computer-controlled six-legged walking vehicle[8] in

1977, with three degrees of freedom per leg. Similar machines were also built at Moscow State University[9] and Ohio State University.[10,11] Since 1978, Hirose and his associates at Tokyo Institute of Technology built a number of four-legged robots.[12] First among these was a quadruped KUMO (spider in Japanese). In 1980, they developed another four-legged walking machine called PV-II (Perambulating Vehicle-II) based on the gravitationally decoupled actuation concept using three-dimensional pantograph mechanisms. An enlarged version of PV-II, the TITAN-III was built in 1984. The name was an acronym from Tokyo Institute of Technology, Aruku Norimono (walking vehicle). One problem with leg mechanism design is the wide difference between the torque and speed requirements during support and transfer phases. Satisfying these requirements using a single actuator often results in more powerful and heavier actuation scheme. As a remedy, Hirose used a dual drive mechanism for leg joints in TITAN-VI. TITAN-VII was designed to assist civil works carried out at steep slope. It used a wire traction mechanism, functionally similar to climbing rope for mountaineers. Latest developed in the TITAN series was TITAN-VIII which was a general purpose walking robot and made as a testbed for other researchers. These robots are commercially available from a private company, Tokyo Precision.

In 1983, the first self-contained machine controlled by an onboard micro-computer was built by Sutherland[13] at Carnegie Mellon University. The ODEX-I[14] was a six-legged walking robot with an axisymmetric leg configuration built by Odetics Inc. The machine was omni-directional due to the circular design. With self-contained power and wireless communications, it was the first commercially available legged robot. The Adaptive Suspension Vehicle (ASV)[6,15] was a six-legged robot designed at Ohio State University for sustained locomotion on unstructured terrain. It carried an operator to provide supervisory commands. A quadruped[16] with three-degree-of-freedom articulated legs was built at National Chiao Tung University, China in 1986. Akizono *et al.* in Japan developed a six-legged walking robot named AQUAROBOT[17] for underwater applications in 1985. Although the performance was not good enough to be used for practical jobs, it was a significant attempt to explore the potential of walking vehicles for underwater and deep sea applications. In 1988, Adachi and his colleagues, also in Japan, developed a quadruped walking robot TURTLE-I[18] using an approximately straight line mechanism for leg motion. A robot leg can provide extensive terrain information as it sweeps through and steps in its environment. Keeping this potential in mind, Attila,[19] a six-legged robot, was built at MIT with pantograph legs in 1990. The robot was extremely rich in sensors (150 sensors in the machine weighing only 3.6 pounds) and was equipped with solar cells to recharge its battery. In 1992, MECHANT (MECHanical ANT), a six-legged hydraulically powered walking robot with pantograph legs, was built at Helsinki University of Technology in Finland.[20] In Spain, a four-legged walking robot RIHMO[21] was built at the Institute for Industrial Automation in 1993. Each leg was constructed using a three-dimensional pantograph mechanism. Later, a modified version RIHMO 2 was built for humanitarian demining operations. The AMBLER,[22] built in 1993 at Carnegie Mellon University, had six legs, arranged in two stacks on central shafts (Figure 7). During normal operation, the machine walked by alternating leg recoveries and body advances. It used to pick up one of the trailing legs for circulating it forward between the two stacks to become a leading leg using *circulatory gait*. Then the robot had to lock the support actuators to propel its body forward. The process repeated, beginning with the trailing leg on the other stack. Recently, at McGill University, Saranli *et al.*[23] built a six-legged robot RHex with C-shaped legs which were made of plastic to provide the necessary springiness and self-stabilization. When the body of the walking robot is a spherically symmetric polyhedron which can be one of the five platonic solids, the robot is termed as platonic. In 1994, Pai *et al.*[24] at University of British Columbia developed a number of *platonic beasts* which were high-degree-of-freedom robots with multi-purpose limbs. These were constructed by attaching a kinematic chain (i.e., a limb) at each vertex

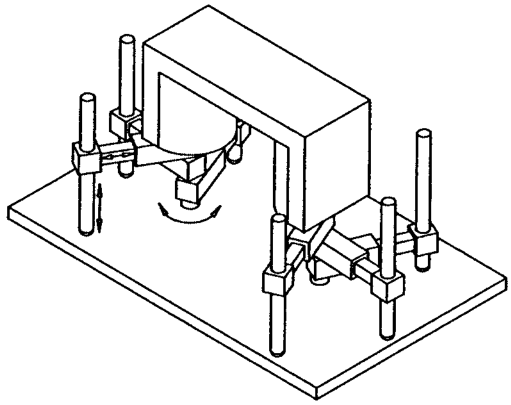

Figure 7. Circulatory walker.

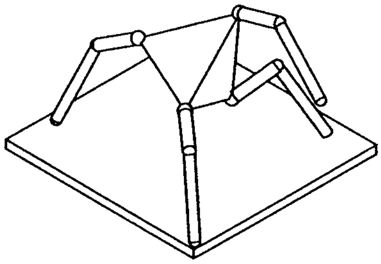

Figure 8. Platonic walker.

of a spherically symmetric polyhedron as shown in Figure 8. Since there was no preferred up direction, these robots were able to recover from loss of footholds.

Using the walking stick insect *Carausius Morosus* as a living prototype, in 1995 Pfeiffer *et al.*[25] developed a six-legged walking robot at Technical University of Munich, Germany. Continuing the research efforts towards biologically inspired walking robots, in 1997, the robotics group at Case Western Reserve University designed a hexapod robot named Robot-III[26] considering the cockroach *Blaberus discoidalis* as a design model. The robot had six pneumatically driven legs supporting a freely translating and rotating body. Initially they made Robot-I, a hexapod with two-degree-of-freedom rod-like legs. Later, in Robot-II, also a hexapod, legs were identical and designed with three degrees of freedom each. However, the three leg pairs were different in Robot-III. The quadruped MEL HORSE-II[27] was developed in 1999 at Mechanical Engineering Laboratory, Japan, with different functions assigned for its front and hind legs. The first industrial walking robot ROWER,[28] a quadruped, at Institute for Industrial Automation of Spain was developed in 1999 for welding jobs in shipbuilding. Later, a six-legged climbing robot REST was built there. In both of these robots, each leg was of SCARA (Selective Compliance Assembly Robotic Arm) configuration and equipped with electromagnetic feet. In the same institute, another quadruped robot SILO4[29] was built for investigation of gaits, force optimization, and control. The four articulated legs of the robot were distributed around the body in a circular configuration. In 2000, Davis *et al.* of University of Salford, UK, developed a biologically inspired quadruped actuated by pneumatic muscle actuators.

Engineering design philosophy suggests that a mechanism designed to be assembled should be disassembled also. Numerous fasteners and fittings that hold different parts together cause major problems, especially in smaller robots. However, natural systems are designed in a different manner. Actuators, sensors, and structural members are compactly packaged and protected from the environment. In a similar way, Clark *et al.* recently developed a six-legged biomimetic robot Sprawlita[30] at Center for Design Research, Stanford University. The robot's servos, wiring, and connectors were embedded within its wax body, using layered-manufacturing technology. Robot Lobster[3] is an underwater remote sensing autonomous legged robot being developed at Marine Science Center of Northeastern University under the DARPA (Defense Advanced Research Projects Agency) biomimetic program. The robot has eight identical articulated legs, each with three degrees of freedom. The joints are actuated by shape memory alloy based artificial muscles.

3.2. Hybrid

Wheeled systems are fast, powerful in terms of load to weight ratio, stable, and easy to control. On the other hand, legged systems can perform tasks in unstructured environments. Hybrid systems were developed to exploit the terrain adaptability of legs in rough terrain and simpler control as well as high speed associated with wheels. From an historical point of view, a vehicle using both legs and wheels was not new, because the wheel barrow, bullock cart, etc. have been used since the early days of civilization. But, legged animals were an integral part of these systems and the design of fully artificial hybrid systems started much later.

In 1983, Ichikawa *et al.*[31] at Energy Research Laboratory of Hitachi, Japan, developed a hybrid locomotion vehicle for nuclear power plants. The vehicle had five locomotion devices, each consisting of a wheel and a leg. The vehicle was not truly autonomous and there is no report of its actual application. In France, Guihard *et al.* designed a hybrid robot called SAPPHYR[32] in 1995, with two free rear wheels and two traction legs. Muscato and Nunnari[33] in Italy developed WHEELEG in 1999. This robot had two pneumatically actuated front legs, each with three degrees of freedom. Two rear wheels were actuated independently. In another effort, a hybrid machine called HYDROBUG[34] was proposed in Australia. It was a six-legged insectlike walking robot equipped with independently driven four wheels. On relatively smooth terrain, all the legs were raised off the ground while the underbody wheels supported the robot, allowing high speeds of up to 50 kmph. In 1999, Krovi and Kumar[35] at University of Pennsylvania

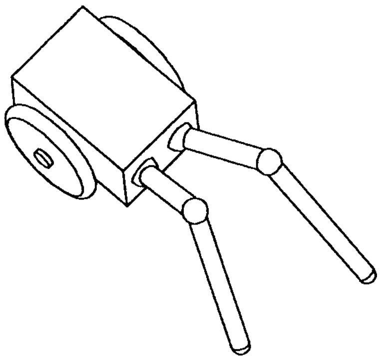

Figure 9. A hybrid walking robot configuration.

developed a hybrid wheelchair with legs and wheels. The prototype had a pair of two-degree-of-freedom planar articulated legs, primarily for use on uneven terrain. At Helsinki University of Technology, Finland, Halme *et al.*[36] proposed a hybrid service robot called WorkPartner using four legs equipped with wheels, each to serve as a foot during walking mode and as a wheel in wheeled mode. At Industrial Automation Institute of Spain, for one hybrid system called Traciminer,[28] using a totally different approach, four leg-type appendages were symmetrically placed around the wheel center to improve traction on poor soil conditions by actuating/deactuating the legs in sequence. ALDURO (Anthropomorphically Legged and Wheeled Duisburg Robot),[37] the hydraulically driven autonomous hybrid vehicle currently being developed at University of Duisburg, Germany, is like a quadruped with two hind feet replaced by wheels. Many of the past prototype hybrid models were installed with active wheels on the body (Figure 9) or on the feet (Figure 10). For hybrid walking robots of the latter category, wheels were heavy and bulky, due to installed actuators for steering and traction. As a remedy, Hirose and Takeuchi[38] proposed a hybrid robot named Roller-Walker with a special foot mechanism in each leg to change between foot sole for walking mode and passive wheel for skating mode. In this system, passive wheels were equipped on the feet of each of TITAN-VIII legs with small actuators for mode changing.

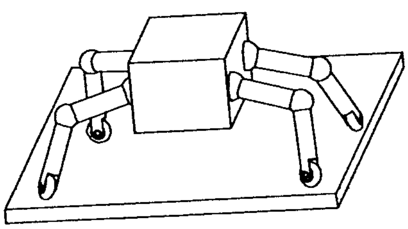

Figure 10. Another scheme for hybrid walking.

In 2000, Halme *et al.*[39] at Helsinki University of Technology developed a hybrid system called Hybtor and introduced the *rolking* mode of locomotion. It has four wheeled legs, each consisting of a three-degree-of-freedom mammal-type leg and a rubber wheel as a foot. Unlike other hybrid locomotion devices, during transfer phase the foot used to support partly and move along the ground by touching it all the time like a blind animal. During supporting phase the wheel operates under speed control or locked and the leg joints generate the propulsion. Each leg operates in force control mode during transfer and it is possible to feel the shape of the ground and detect obstacles. The advantages of rolking mode compared to normal walking are better speed and stability. Speed is improved because no time is wasted for lifting and lowering the foot in the walking cycle. Stability will not be easily lost because the leg can be instantly switched to supporting state whenever required. However, the complications of this mode of locomotion is that any leg can be moved only along the direction of the corresponding wheel rotation.

3.3. Twin Frame

Walking machines with three degrees of freedom for each leg have the flexibility to select a suitable foothold in three-dimensional space. Although joint motions were coordinated by software in a terrain-adaptive walking machine, it becomes very difficult to control during body propelling motion, because a cooperational actuator control in supporting legs is required for the system with several closed kinematic chains between the body and the ground. If it is possible to decouple motions and to realize body propelling motion by only one degree of freedom, the control system will become simpler. Most of the projects in this group were planned mainly to avoid the problems associated with the coordination and control of large number of motions. However, reducing degrees of freedom may be effective in simplifying control; the terrain adaptability becomes poor due to grouped placement of legs.

In 1969, the largest off-road vehicle in the world,[6] a coal mining dragliner called Big Muskie, was built by the Bucyrus-Eric Company. The vehicle weighed 27 million pounds and had four hydraulically powered legs, one at each corner of the machine. During normal mining operations, Big Muskie rested on a cylindrical base 105 ft in diameter. During walking, the

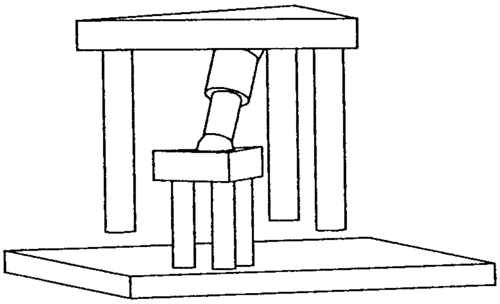

Figure 11. Twin frame walking robot.

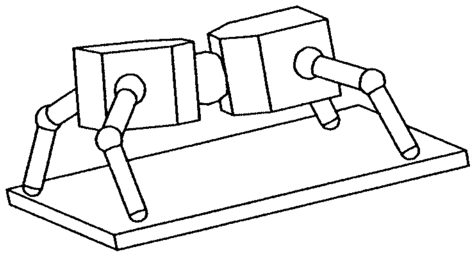

Figure 12. Configuration of walking robot with body articulation.

machine utilized 24 electric motors of 600 hp each to provide hydraulic power for raising the base off the ground while transferring the weight of the machine to four feet. Once raised, a second set of actuators was used to move the machine to keep it again upon its base. Kaneko *et al.* in Japan built an eight-degree-of-freedom hexapod walking robot MELWALK-III[40] in 1985. It had a basic leg motion for body propulsion and additional freedoms for terrain adaptation. This walking machine had two plates, each equipped with three legs. The plates were designed with provision to rotate relative to each other around the vertical shaft. In 1993, an eight-legged tele-operated walking robot named Dante[41] was developed at Carnegie Mellon University to explore an active volcano. The eight pantographic legs were organized in groups of four, on an inner frame and on an outer frame. After the legs of one frame simultaneously lifted, the frame slid forward and then lowered for the next step while the legs of the other frame supported the body. The frames were able to rotate with respect to each other to change the direction of movement. The improved version, Dante-II,[42] used a tether to support itself on steep terrain in an arrangement similar to the wire traction mechanism used by Hirose in TITAN-VII. Recently, Ota *et al.*[43] at Tokyo Institute of Technology developed a walking robot named ParaWalker-II with reduced degrees of freedom. It had two leg bases each connected to three legs and able to support the robot statically. The schematic diagram of the arrangement is shown in Figure 11. The leg bases were connected by a six-degree-of-freedom mechanism which helped the robot to walk by moving each leg base alternately like a biped.

3.4. Articulated Body

The rigid structure of the body restricts adaptability of the machine to terrain irregularities. The mobility during rough terrain locomotion can be improved by making the body flexible as observed in natural walkers. However, control of these systems becomes more and more complex as the order of body articulation increases.

For better agility by allowing the central body to follow the terrain profile, in 1999, Doroftei and Preumont[44] of Belgium developed a hexapod called IOAN which consisted of three body segments connected by two universal joints. Each body segment had two legs each with two active and one passive degrees of freedom. Recently, Berns *et al.* in Germany built a biologically inspired four-legged robot BISAM.[45] In this robot, the main body was with three segments. The front and rear segments, each equipped with two mammal type legs, were connected via two-degree-of-freedom joints with the middle segment. The schematic diagram of a walking robot with body articulation is shown in Figure 12.

4. LEG MECHANISM

An autonomous walking robot has to carry all its subsystems including power supply unit onboard rather than being connected by tethers. Although the leg of a walking robot has similar structure as a robot arm, the design requirements are quite different. Most challenging is the very high payload to self-weight ratio required for a leg. Just to have an idea, let us consider an N-legged walking robot with identical legs and the weight of each leg be w. Even with conservative estimate, if the weight of the control hardware, chassis, power supply, and other subsystems is assumed to be equivalent to Nw, the total machine weight becomes $2Nw$. For statically stable walking, at any instant a minimum three legs (one leg of one side of the longitudinal body axis and the two of the other) should be on the ground and, during such support states, for static equilibrium of the machine, one leg has to carry half of the total machine weight, i.e.,

Nw. During walking, a four-legged walking robot places its weight on three and four supporting legs alternately. Thus, it implies that in each locomotion cycle, there are instances when any leg has to carry a load that can be as high as four times the leg's own weight. Of course, for robots with more than four legs, there are other gaits for which loading on each leg will be less but the maximum load (when supported by three legs) on any leg can be six and eight times the individual leg weight for six- and eight-legged robots, respectively. This will be even higher depending on the payload on the robot. In contrast, a robot arm generally carries a small fraction (as low as 10%) of its own weight.

A variety of leg geometries can provide the motion required by a terrain adaptive walker. Some of these mechanisms which are already tried are discussed next.

4.1. Straight Line Mechanism

Straight line mechanisms make it possible to realize body-propelling motion by one degree of freedom. With reduced degrees of freedom the control system becomes simpler. However, straight line linkage mechanisms have disadvantages like complex arrangement of links and restricted workspace. Terrain adaptability also becomes poor with such systems. Legs in hexapod walking robot MELWALK-III[40] were four bar linkage mechanisms to generate approximate straight line motions. Two sets of parallelogram linkages were used to constantly maintain the leg perpendicular to the body. In a separate mechanism, vertical foot motion was provided using rack and pinion through non-back-drivable worm gearing. Song *et al.*[46] explored seven bar straight line mechanism for better energy efficiency of walking robot. Adachi and his colleagues used an approximately straight line three bar mechanism as the leg for their quadruped walking robot TURTLE-I.[18]

4.2. Articulated

Articulated legs have the advantage of large workspace. Legged animals in nature have this type of leg. The arrangement of two coincident hip joints has the advantage of placing two of the leg actuators on or close to the vehicle body, so that their mass is not carried by the leg during foot transfer. Also, the perpendicular arrangement of joint axes at the hip provides optimum leg workspace and simplifies the leg kinematics. There are two variations of this leg: insect-type and mammal-type. In the insect-type leg, the knee joint is located laterally or at a position higher than the hip (Figure 13), whereas, in mammal-type legs, the knee joint is placed under the hip (Figure 14).

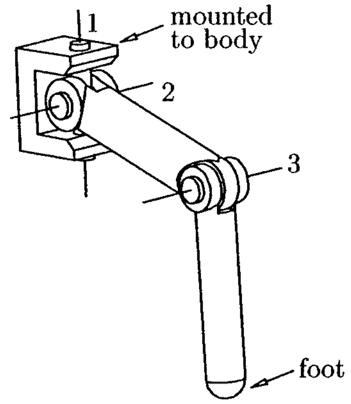

Figure 13. Insect type articulated leg.

Each leg of the OSU hexapod[10,11] built by McGhee and his associates had three joints, two at the hip and one at the knee. Non-back-drivable worm gears were used to ensure locking of joints when power is disconnected. Okhotsimski *et al.* at Moscow Physico-Technical Institute used three-degree-of-freedom articulated legs for their six-legged walking vehicle.[8] Another hexapod of similar leg configuration was built by Gurfinkel *et al.*[9] at Moscow State University. In a hexapod by Sutherland[13] at CMU, the leg was connected to the body at the hip by the universal joint. This type of leg was also used in the NCTU-quadruped.[16] In AQUAROBOT,[17] all the driving devices were installed inside the legs and made watertight. Two-dimensional planar legs were used in hybrid wheelchair.[35] Robot Lobster[3] used three-degree-of-freedom articulated legs in which the joints

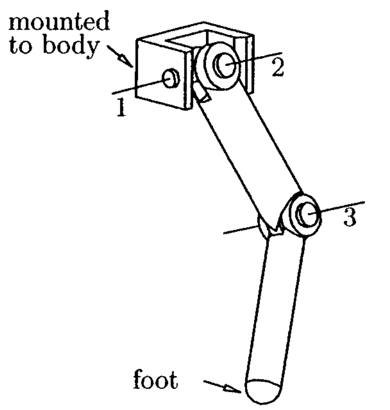

Figure 14. Mammal type articulated leg.

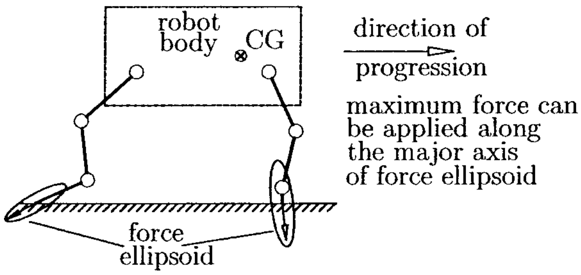

Figure 15. Redundant articulated leg.

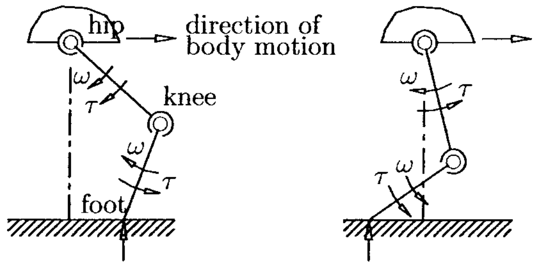

Figure 16. Negative work in articulated leg.

were driven by muscle actuators. Inspired by superior locomotion performances of legged animals, researchers considered biological design concepts to apply these or similar mechanisms to the technical design of walking machines. The TUM walking robot[25] consisted of a central body and six legs, each with three segments. As in the walking stick insect, the segments of each leg were in a common plane and were connected to the central body by a pivot joint with an inclined axis around which the leg plane was able to rotate freely. According to Full and co-researchers,[47] in the cockroach, the rear legs are large and powerful, and drive the insect forward. Middle legs are used for supporting the body weight, turning and lifting the body to climb over a barrier. These legs function like struts. Front legs are used as a brake. Like the cockroach, in the biologically inspired machine Robot-III,[26] each leg was composed of three segments. To achieve differing functions like cockroach legs, the robot was designed with five degrees of freedom in the front legs, four in the middle, and three in the rear legs. The legs of the quadruped robot MEL HORSE-II[27] were designed with redundant actuated joints. Articulated chain with redundancy has the potential to improve the force/velocity transmission characteristics in any specified direction by appropriately aligning its posture.[48] Utilizing this property, front legs were designed with a configuration to withstand vertical load. Similarly, the hindlegs were designed for generating force in the horizontal direction to push the body forward. The concept is illustrated in Figure 15. The legs in the biologically inspired quadruped BISAM[45] were mammal-type and designed with four segments each, connected by three parallel revolute joints. Each leg was connected to the main body by a fourth revolute joint. In the hybrid robot ALDURO,[37] each leg was designed anthropomorphically with a three-degree-of-freedom spherical hip and a revolute knee. In Hybtor,[39] also a hybrid robot, each limb was made of a three-degree-of-freedom mammal-type leg and a rubber wheel as the foot. The quadruped SILO4[29] was made of three-degree-of-freedom articulated legs, each equipped with a passive three-degree-of-freedom foot. The biological quadruped chosen as inspiration for the quadruped[49] at University of Salford, UK, was the greyhound dog. Each of the three leg joints were powered by an antagonistic muscle group.

Articulated leg designs are often responsible for poor energy efficiency of the robot due to geometric work loss. For walking on flat terrain without moving the vehicle center of gravity up and down, no net power (except to overcome friction) is required because the body motion is perpendicular to the direction of gravitational force on the machine. But, if some actuators consume power, the rest of the actuators need to generate negative power. An actuator generating negative power means mechanical work is being done on it. Waldron and Kinzel[50] explained that one reason behind the poor energy efficiency of walking robots is due to the use of the actuators as brakes. The energy consumed when the actuator is back-driven is converted into heat with no provision for recycling. Figure 16 shows a two-link articulated leg with independent joint actuators. In Figure 16(a), the foot is ahead of the hip and the actuating torque at the hip is in the same direction as the angular speed of the hip joint. Thus the hip actuator is doing positive work, whereas the knee actuator does negative work because the actuating torque at the knee opposes the hip rotation. In Figure 16(b), the foot is placed behind the hip and the hip actuator does negative work whereas the actuator at the knee does positive work. In both of these configurations, the algebraic sum of the work done by the hip actuator and the knee actuator is zero. This type of loss is associated with the leg geometry and known as geometric work loss. It is difficult to regenerate negative power using current actuator technologies, and the generation of negative power must be suppressed for good energy efficiency.

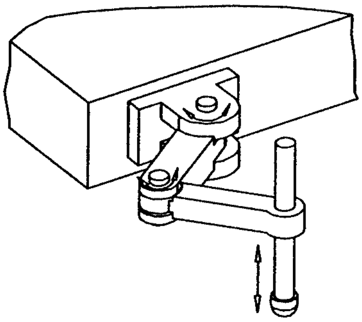

Figure 17. Leg with SCARA configuration.

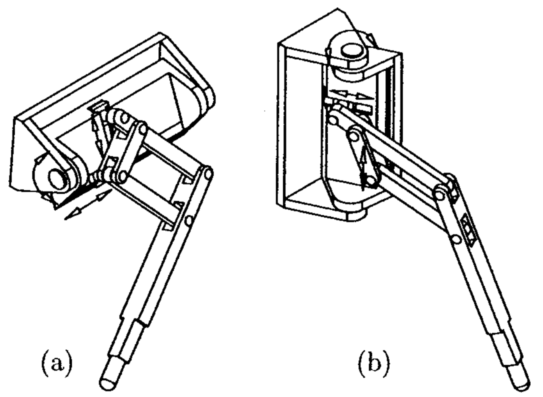

Figure 18. Legs based on two-dimensional pantograph mechanism.

4.3. Gravitationally Decoupled

One method is to decouple the leg actuators that propel the body from the actuators supporting it during propulsion. Thus, negative power can be eliminated by ensuring that the load-bearing actuators do not move and the actuators which move do not bear load. A number of leg mechanisms were used in the past to realize such gravitationally decoupled actuation.

4.3.1. Orthogonal

The legs of six-legged planetary rover AMBLER[22] developed at Carnegie Mellon University were orthogonal RPP (rotational-prismatic-prismatic) mechanisms that decoupled horizontal and vertical motions. As shown in Figure 7, each leg consisted of a rotary link, an offset extension link, and a support link. A freely rotating foot pad was attached at the base of each support link.

Each locomotion unit in the hybrid machine by Ichikawa *et al.*[31] was made of a supporting rod with a wheel attached at the end. There were three degrees of freedom per leg: leg lifting, steering, and wheel rotation. In ROWER and REST,[28] each leg was of SCARA configuration (Figure 17), with two rotational joints and one prismatic which held the foot.

4.3.2. Two-Dimensional Pantograph

As mentioned earlier, it was difficult to coordinate a large number of motions. Efforts were made in the past to simplify leg mechanisms as much as possible. In some machines, a two-dimensional pantograph mechanism was used to provide straight line foot motion along the forward and vertical directions. Foot motion in the lateral direction (if any) was due to rotation of the leg about an axis parallel to longitudinal body axis [Figure 18(a)]. In others, the leg was designed for motion in the vertical plane which can rotate about the vertical hip axis [Figure 18(b)]. The four legged robot by Taguchi *et al.*[7] used two-dimensional pantograph mechanisms driven by binary actuators. For better terrain adaptability, both the foot motions were provided with many stopping positions. In ODEX-I[14] by Odetics Inc., each leg had three degrees of freedom. The leg was a planar modified pantograph mechanism. Also in the Adaptive Suspension Vehicle (ASV),[6,15] the legs were planar pantograph mechanisms. The third degree of freedom was provided by swinging the entire leg assembly laterally about an axis parallel to the longitudinal body axis. Attila[19] used two-dimensional pantograph legs with the third degree of freedom as hip rotation about the vertical axis. A fourth global dof was provided for rotation of all six legs about their axles together to ensure that legs remain always vertical. Also, a pantograph mechanism was used for MECHANT[20] developed at Helsinki University.

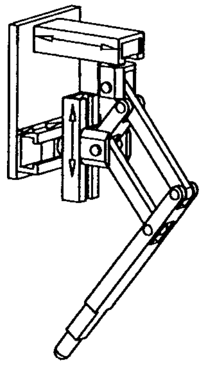

Figure 19. Three-dimensional pantograph leg.

4.3.3. Three-Dimensional Pantograph

In the three-dimensional pantograph, all the three motions are linear (Figure 19). Hirose and his group at the Tokyo Institute of Technology used a three-dimensional pantograph mechanism for gravitationally decoupled actuation in the four-legged walking machine PV-II.[51] The robots in TITAN family were also built with this type of leg. A dual drive mechanism was introduced in TITAN-VI[52] to achieve high foot speed during transfer phase. The four-legged walking robot RIHMO[21] was constructed using a three-dimensional pantograph mechanism.

The most important feature of the pantograph mechanism is that geometric work loss can be completely eliminated. Unfortunately, this approach eliminates geometric work loss, only if the tangential ground reaction forces do not exist. But it is found that there are advantages to be gained from operating legged systems with foot force components in the tangential plane.[47,53] Also important is the mechanical design complexity particularly in three-dimensional pantographs because such leg designs require one pivot of the mechanism to have a compound slider.

5. UNEXPLORED AREAS

5.1. Variable Transmission

Conventional drives, particularly electric motors, have high electro-mechanical conversion efficiency only when the operating conditions like speed and load are close to their nominal values. However, for walking robot leg joints, torque to be generated by the motor depends upon the gait, payload, and terrain. The motor speed is much less than nominal during the major part of the locomotion cycle. All these factors lead to nonrational energy expenses. Another problem with leg mechanism design is the huge difference between the torque and speed requirements at joints during support and transfer phases. Joint actuators require generation of high torque at low speed during support but low torque at high speed during transfer phase.

So far, almost all leg designs used a single actuator per joint with fixed reduction between the actuator and the joint. With same actuator-reducer combination for a joint during support as well as transfer, the weight of the driving unit increases and, due to cascading effect on other actuators, the overall leg weight increases dramatically. To avoid this problem, between 1990 and 1994, Hirose and Yoneda[52] built a quadruped walking machine TITAN VI using a dual drive mechanism. It was done by the vertical axis drive system using a low reduction ratio motor that was always connected, and during support phase, low speed, high torque movement was supplemented using a clutch to connect the high reduction ratio motor. Similarly, Inagaki *et al.*[54] proposed a two-state variable transmission mechanism by using a pair of electromagnetic clutches. Depending on the reduction requirement, one of the two clutches was engaged. Although this important aspect of artificial leg design is well recognized[55] and some works were done as mentioned above, more investigations are required to solve this problem without increasing the control complexities, particularly during rough terrain locomotion.

5.2. Regeneration

One important aspect of an autonomous walking robot is energy efficiency. Geometric work loss is identified as one major source of losses in artificial legged systems. When external work is pumped into an actuator without regeneration it dissipates as heat. A similar problem occurs in nature also. Although during running and hopping, animals use elastic body elements to store part of such negative work to use during the next step,[56] such storage and subsequent recovery is not effective during walking at low speed. Evolutionary process has not yet come up with a mechanism for storing mechanical energy for indefinite periods and releasing it later at a controlled rate. But man has a somewhat better solution using a spring or a combination of electric generator and storage battery, etc. Dhandapani and Ogot[57] studied the feasibility of spring-damper systems within the limbs of a biped walking robot to transfer a portion of the energy typically dissipated from one step to the next. Although they claimed positive results, it was not pursued further. In another effort, Shin and Streit[58] introduced a mechanical equilibrator by connecting two out-of-phase legs by tension spring to reduce the actuating force. But such a system requires a complicated control algorithm even for flat terrain walking. Another method for improving efficiency is through regeneration of energy dissipated in an actuator.[59] However, no work has been reported so far using such regenerative actuator concepts.

5.3. Redirection

An alternative strategy is by redirecting the body weight. This can be accomplished by a mechanism that converts gravitational force on the robot to a force at a right angle to push the vehicle forward.[60] This principle is utilized successfully in the bicycle. When the rider places the body weight (during pedaling while standing) on the pedal, the center of gravity falls and the cranks, sprockets, chain, and rear wheel constitute a mechanism that converts the vertical fall of the rider to a forward motion. A bird's wing is also based on this principle and generates large force components in the direction perpendicular to the wing's motion. In spatially decoupled leg designs, although the negative work is eliminated, the actuator for vertical foot motion remains energized to prevent the body from falling. With non-back-drivable transmission, continuous energization of an actuator can be avoided, but this type of transmission causes problem during active force control. However, irrespective of transmission, in the existing designs, the load on the foot cannot be utilized to propel the body froward.

5.4. Balancing Vehicle Weight

The most important design requirement for a walking robot is the high load-bearing capacity of its legs compared to their own weight. One method worth exploring is reducing the gravitational forces acting on the body. Fishes balance the gravitational forces by the swimbladder. A similar approach can be utilized for artificial walking systems also. Once the load on each leg is reduced, the leg design will be simple like any manipulator. In such a condition, the only challenge for the robot will be to coordinate its legs for propelling the body forward.

6. RECENT TRENDS

Recently, in a number of projects[25,26,30] focus was on biological design approaches. However, there are important differences between engineering and biology. Legs in nature have many more degrees of freedom than current legged robots. For natural systems, the motion in joints to propel the body is mechanically complex. For example, as a joint rotates, the mechanical advantage of the muscle on the joint changes.[61] Muscle is a far more powerful and efficient actuator than the best electric motor currently available. Also important from an energy efficiency point of view is that animals have both slow and fast muscles. Slow fibers are more energy efficient at low speed of contraction whereas fast fibers are recruited at higher speed for better efficiency.[62] Biological legs are extremely rich in sensors[63] for information about position, speed, force, etc., which helps to optimize gaits[64] and foot force patterns.[47] Also, it is important to note that the requirements of natural systems include many aspects like growth, reproduction, and metabolism, which need not be considered for robot design. Finally, direct copying of configuration, actuators or control may be impractical because the resources biology uses are different compared to those used by engineers.

Apart from mechanical design, the other important aspect in legged locomotion research is control. The coordination problems between many legs of statically stable machines and advances in control engineering lead to the development of walking robots with fewer legs like bipeds. Many research groups worldwide are working to develop robots that are one step closer to science fiction's androids. Also important is that in human environments or to assist elderly and disabled people, it is natural to interact with humanlike robots. In 1972, Kato *et al.*[65] at Waseda University of Japan developed a number of bipeds and, in the 1980s, Raibert and colleagues[66] at MIT and CMU developed running bipeds and even hopping monopods. Although these robots are far from their fictional counterparts in performance, such efforts contributed significantly in improving the performance of dynamically stable walking robots. Since then, numerous efforts were made and most sensational was the development of the Honda humanoid robot[67] in Japan. This robot demonstrated the ability to move forward and backward, walk up and down stairs, and perform simple operations.

7. CONCLUSION

Most of the design approaches pursued to realize statically stable artificial walking are reviewed in brief. Although, over last few decades, legged robots are the focus of many research groups, current robots are still far from achieving the performance of their biological counterparts. There are hundreds of walking robots at present all over the world, but it is not known how many of these robots are actually installed for practical applications. Some may argue that biological approaches will help, but, so far, the performance of biologically inspired systems is no different. Moreover, nature's way may not be the only way, or even necessarily the best way. For example, a biologically inspired approach applied to artificial flying (or flapping) machines ended in disaster. Breakthrough came only when a fundamental shift towards the science of aerodynamics took place. Of course, natural flying systems helped in improving performance. It may be possible that an equivalent science is lacking in the area of artificial legged locomotion.

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