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A Comprehensive Study of Climbing and Walking Robots (CLWAR) Paradigms

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ABSTRACT

There are quite a number of naturally dangerous, expensive and hostile practices that are inimical and hazardous to the general health of human beings. Typical examples of such practices include emergence rescue mission, mineral exploration, planetary exploration, scaffolding, construction, painting of high rise buildings, surveillance as well as reconnaissance in urban environments. The use of human labor in these activities poses a high risk of accident which may result in fatalities and even death. One of the promising solutions to this problem is the use of climbing and walking robots (CLWAR). A CLWAR is typically defined as a mobile robot that possesses manipulative, perceptive, communicative and cognitive features which enable it to perform in diverse environments such as medicine, transportation, engineering as well as Information and Communication Technology (ICT). A CLWAR has two basic characteristics. These include locomotion and adhesion. With respect to locomotion, a CLWAR can be legged, winged, wheeled, tracked, crawling or hybrid. Adhesion refers to the ability of the robot to attach itself to surfaces such as walls, floors, glasses and ceilings. This is usually done by using adhesive mechanisms such as suction force, magnetic force, ropes, grippers and van der Waals forces. Nevertheless, the use of CLWAR is limited because their performances are usually unsatisfactory. This is because they are still bedeviled by locomotion and adhesion challenges. Hence, this paper comprehensively examines the typical examples of CLWAR, their applications in diverse domains as well as their challenges. This paper also considers the biologically inspired principles of locomotion and adhesion in CLWAR. The paper recommends that the environment, structure of the robot and the type of tasks to be performed by the robot are some of the factors to be considered during the design of a CLWAR.

General Terms

Artificial Intelligence, Robotics

Keywords

Adhesion, CLWAR, locomotion, mobile robot

1. INTRODUCTION

Climbing and Walking Robots (CLWAR) have been widely deployed in almost all human endeavours for providing services to human beings. Such services are usually rendered for industrial purposes to ensure safety in quite a number of tasks that are too dangerous for human beings to perform [1], [2]. Typical examples of such tasks include the cleaning of the outer walls of high buildings, construction work, scaffolding, painting of large vessels, emergence rescue mission, mineral exploration, planetary exploration, surveillance, reconnaissance in urban environments and inspection of storage tanks in nuclear power plants [3]. One of the major challenges involved in the performance of these tasks is the high risk of accident which may result in casualties and even death. For instance, Luk et al. [4] emphasized that the traditional method of maintaining and inspecting large buildings entails the installation of costly scaffoldings or gondolas which requires workers to stand on them in mid-air and at high altitude. Unfortunately, Nansai and Mohan [5] reported that a gust of wind once resulted in a situation where a gondola became uncontrollable at Shanghai World Financial Center. In view of this, quite a number of CLWAR have been developed to resolve this difficulty.

There is no universal definition for CLWAR [6]. However, Behnam [7] defines a CLWAR as a robot that possesses the capabilities of manipulation, perception, communication as well as cognition which make it possible for it to perform numerous tasks in both industrial and non-industrial environments. CLWARs are special types of mobile robots which possess two major characteristics; these include locomotion and adhesion [3]. Locomotion refers to the ability of a CLWAR to move from one place to another either through legs, wheels, tracks or wings. Legged CLWARs use mechanical limbs for their movement. They are biologically inspired by human beings, animals and insects. Wheeled CLWARs move on the ground with the aid of wheels, tracked robots employ tracks for their movement while flying or winged robots move with the aid of wings. These locomotion mechanisms support crawling, flying, rolling, walking, dancing, climbing and jumping. Adhesion on the other hand is the ability of a CLWAR to attach itself to diverse surfaces such as walls, glasses, floors and ceilings. Typical examples of mechanisms that support adhesion in CLWAR include suction force, magnetic force, ropes, grippers and van der Waals forces [3]. Suction force involves the use of vacuum cups on each of the CLWARs feet in order to prevent loss of pressure resulting from surface irregularities [8]. Magnetic force involves the use of magnets or electromagnets to attach to surfaces [9]. Robots using van der Waals force mimic a gecko’s dry adhesion [3]. Rope climbing robots adhere to surfaces with the aid of ropes while robots that use grippers for adhesion use gripping systems for attaching to surfaces [10].

Interestingly, the last decade has witnessed a great interest in CLWAR. This has however led to the development of diverse prototypes of CLWAR for different applications. Nonetheless, the use of CLWAR is still limited because their performances are usually unsatisfactory. This is chiefly because the problem of locomotion and adhesion still exists in CLWARs [11]. In addition, the cost of developing CLWAR is very high. In view of this, this paper critically examines the applications and challenges of CLWAR. The paper also appraises the principles of locomotion and adhesion in CLWAR.

This paper is organized into the following sections: section 2 is the general overview of CLWAR; section 3 deals with the locomotion principles in CLWAR. Section 4 presents the principles of adhesion in CLWAR. Section 5 examines the applications and challenges of CLWAR while section 6 recommends the factors that should be considered during the design of a CLWAR. Section 7 concludes the study.

2. OVERVIEW OF CLWAR

There is no general definition for CLWAR. Nonetheless, a CLWAR is generally defined as a mobile robot that possesses manipulative, perceptive, communicative and cognitive features which enable it to perform in diverse environments such as medicine, transportation, engineering as well as Information and Communication Technology (ICT). A CLWAR can also be described as a special type of mobile robot that have an adhesive mechanism and also exhibit the capability to move from one place to another either through legs, wheels, tracks or wings. Guo et al. [12] concisely defined a CLWAR as an unusual mobile robot that exhibit energy, autonomous behavior, have a robust and efficient adhesion mechanism, an agile locomotion mechanism and intelligent sensors integrated together such that they can adapt to various wall surfaces and 3-Dimensional terrains to conduct given tasks. A CLWAR possesses two basic characteristics. These include adhesion and locomotion. Adhesion is the ability of a CLWAR to attach itself to surfaces such as walls, floors, glasses and ceilings. This is usually done by using adhesive mechanisms such as suction force, magnetic force, ropes, thrust force, grippers and van der Waals forces. Locomotion, on the other hand, refers to the ability of a CLWAR to move from one place to another though legs, wheels, tracks, wings or a combination of two or more locomotion mechanisms. CLWAR can also move using the brachiating bio-inspired locomotion principle. This form of locomotion allows a CLWAR to swing and use energy to grab and release surfaces. This form of locomotion is similar to an ape that is swinging from one tree to another.

Locomotion mechanisms are necessary in CLWAR to support crawling, flying, rolling, walking, climbing, dancing and jumping. There are three core issues that are vital to the locomotion of any mobile robot. These concepts include stability, the characteristics of the ground contact and the type of environment the robot moves in [13]. Stability is important in CLWAR because it is required for balance and thus will not allow the robot to overturn. Stability can either be static or dynamic [14]. A robot is said to be stable statically when the robot has no motion at a particular moment of time [15]. A static robot has at least three points of contact with the ground. However, a robot is tagged dynamically stable if it actively balances itself to prevent overturning. Dynamically stable robots have relatively small footprints because only one foot has ground contact during walking. The characteristics of the ground contact is a function of the type of contact that a robot makes with the ground such as footprints, the angle of contact to the ground and the friction between the robot and the ground surface [14,16]. The robot environment refers to the structure or nature of the medium through which the robot moves. This could be through water, air or ground which could be flat, hard or rough [14].

3. PRINCIPLES OF LOCOMOTION IN CLWAR

This section discusses the principles of locomotion in legged, wheeled, tracked, crawling flying and hybrid CLWAR.

3.1 Locomotion in Legged Robots

CLWAR that move with legs are referred to as legged robots. Legs provide dexterous locomotion. Legs also provide better mobility in rough terrains because they use isolated foot holds that optimize support and traction [17]. For a robot to move a leg forward, it must have at least two degrees of freedom (DOF), that is a lift and a swing action. Hence, the more the number of legs, the more stable a CLWAR tends to be while fewer legs tend to greater maneuverability. In addition, the number of limbs determines the available gaits. Literarily, gait refers to the pattern of movement of the limbs of animals or humans during locomotion. Shival et al. [16] defines gait as a human like walking posture which enables legged robots to move in a more stabilized and balanced manner. It can also be viewed as the way of walking and the rule that coordinates the operation of each leg [18, 19]. Roland [13] also defines a gait in robotic terms as a periodic sequence of lift and release events for each leg. A gait is also viewed by Liu and Jing [19] as a way of walking and the rules that are involved in coordinating the operation of each leg. According to Roland [13], if a robot has k legs the number of possible events N is given as shown in equation (1):

$$N = (2k - 1)! \qquad (1)$$

For instance, a robot with two legs will have 6 numbers of possible events while robots with 6 and 8 legs will have 39916800 and 1307674368000 number of possible events respectively. Hence, the more number of legs a robot has, the more complex the limb coordination. The Central Pattern Generators (CPG) however plays an important role in limb coordination. According to Marder and Bucher [20], CPGs are neuronal circuits that produce rhythmic motor patterns such as walking, breathing, flying and swimming when activated. This is usually done in the absence of sensory or descending inputs that carry specific timing information [20]. The basic advantage of legged robot lies in their ability to overcome uneven surfaces [4]. They are however slow and heavy and their control system is complex due to their gait [21]. Furthermore, the major challenge of legged robots include the problem of navigating and avoiding obstacles in real-time and in real environment.

Deshmukh [22] pointed out that an ideal walking machine must have a uniform velocity whilst the feet are in contact with the ground and its stride/gait must also be lengthy in relation to the physical dimensions of the walking robot in order to attain adequate speeds. Furthermore, the height and length of the robot's stride must be controllable by an operator and the height of the step must be large compared with the dimensions of the robot. The feet of the robot should also have a high stride to return-time ratio. Deshmukh [22] also emphasized that the mechanism integral to the legs of the robot must be provided for steering the body of the robot. Furthermore, the body of the robot must be capable of moving either in the forward or reverse directions while the inertia forces and torques of the robot must be balanced and the energy lost in lifting the foot of the robot must be recovered in lowering the foot. In addition, the height of the body of the robot above the ground should be controllable by an operator [22].

Legged robots are usually inspired by nature and they are of various types [23]. Legged robots include one-legged robots, two-legged robots, three legged robot, four-legged robots, six-legged robots and eight-legged robots.

3.1.1 Hopper or One-Legged Robot

This is also referred to as pogo stick or mono-pedal robot. Hence, one-legged robots possess only one leg which they use for navigation. One-legged robots require a single point of ground contact which allows them to travel in rough terrains [16]. Typical example of a one-legged robot is the one leg hopper developed by Marc Raibert in Massachusetts Institute of Technology (MIT) in 1983. Another example of a one legged robot is the Berkeley's Salto developed in the University of California, Berkeley. One-legged robots use hopping motion for navigation. The major challenge with one-legged robot according to Böttcher [16] is the coordination of the leg for locomotion. This is because the number of gaits in one-legged robot is one. Figure 1 shows the one leg hopper.

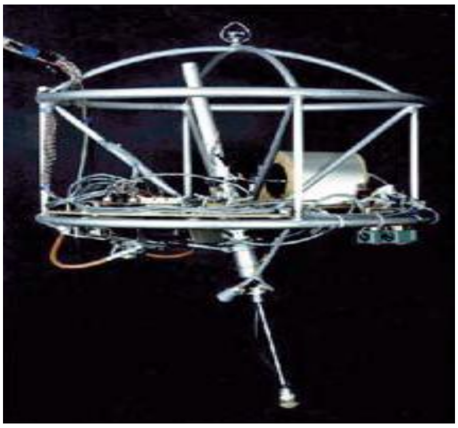

Fig.1: One-leg hopper [24]

3.1.2 Biped or Two-Legged Robot

The two legged robot is also known as bipedal robots. Two-legged robots have two legs which they use for locomotion. Most two-legged robots are biologically inspired by human beings. However, some bipeds do not take the shape of human beings. For instance, Takita et al. [25] designed a biped robot whose structure is inspired by dinosaurs. In addition, Jongwon [26] designed a biped that is biologically inspired by a domestic cat. However, two-legged robots can walk, run, jump, dance as well as move up and down stairs. Bipedal robots have 6 numbers of possible events. These events include the following Lift left leg/ Release left leg/Lift right leg/Release right leg/Lift both legs together/Release both legs together [16]. The advantages of bipedal robots include their ability to move in areas that are usually inaccessible to wheeled robots, such as stairs and areas littered with obstacles. Again, bipedal robots cause less damage on the ground when compared with wheeled robots. Bipedal robots are dynamically stable because they have two points of contacts with the ground. Hence, research in bipedal robots has dawdled because of the complications involved in establishing stable control [27]. There is however no general approach to solving this problem. Nevertheless, the different approaches used to solve this problem are based on Zero Moment Point (ZMP). The ZMP was originally introduced by Vukobratovic and Juricic [28]. The Zero Moment Point (ZMP) is described in robotics by Vukobratovic and Borovac [29] as the point on the ground where all momentums or active forces are equal to zero. The ZMP as described by Vukobratovic and Borovac [29] is as illustrated in equations (2) and (3).

$$x_{zmp} = \frac{\sum_i m_i(z+g)x_i - \sum_i m_i x z_i - \sum_i I_{Iy}\theta_{iy}}{\sum_i m_i(z+g)} \quad (2)$$

$$y_{zmp} = \frac{\sum_i m_i(z+g)y_i - \sum_i m_i y - \sum_i I_{Ix}\theta_{ix}}{\sum_i m_i(z+g)} \quad (3)$$

In equations (2) and (3) above, $(0, x_{ZMP,\ yZMP})$ are the ZMP coordinates in the Cartesian coordinate system, (x_i, y_i, z_i) is the mass centre of the link i, m_i is the mass of the link i, and g is the gravitational acceleration. I_x and I_y are the inertia moment components, θ_{ix} and θ_{iy} are the angular velocity around the axes x and y .

In spite of the problem of stability in bipedal robots, quite a number of successful bipedal robots have been developed for climbing diverse surfaces with different slopes [30]. Typical examples of bipedal robots include Advanced Step in Innovative Mobility (ASIMO), the WABIAN robot (WAseda BIpedal humANoid) and the First Reconfigurable Adaptable Miniaturized Robot (RAMR1), a biped climbing robot. Figure 2 shows the image of the RAMR1.

Fig. 2: RAMR1 biped climbing robot [31]

3.1.3 Three-Legged Robot or Tripedal

These are robots with three legs. However, these types of robots are not common because they are not biologically inspired by humans, animals and insects. A typical example of this type of robot is the self excited dynamic experimental robot (STriDER) developed in Romela Lab [32]. This is as shown in Figure 3. STriDER is usually likened to a bipedal robot with a walking stick. It has a swing walk because it walks by shifting its weight on two of its legs and falls forward away from the third leg, its body then flips upside down and the third leg swings between the two [32]. The simple tripedal gait of STriDER makes it more advantageous than other legged robots. It has a simple kinematic structure; it is inherently stable, simple to control and energy efficient [33].

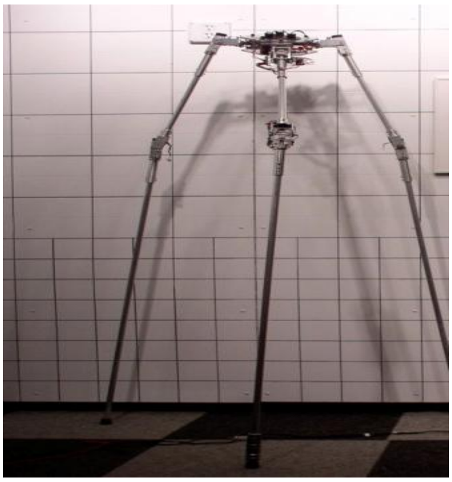

Fig. 3: STriDER [33]

3.1.4 Four-Legged Robot or Quadruped

The quadruped robots have four legs and they are biologically inspired by four legged mammals. A typical example of a quadruped is AIBO shown in Figure 4. Quadruped robots are more stable than bipedal robots during movements because they move one leg at a time while ensuring a stable tripod. However, some quadruped robots are dynamically stable.

Fig 4: AIBO [34]

3.1.5 Six-Legged Robot or Hexapod

Hexapods are programmable robots with six legs attached to their bodies [35]. Hexapods are biologically inspired by ants. One of the advantages of hexapods is their ability to climb over obstacles that are larger than their equivalent sized wheeled or tracked vehicle [35]. They have greater mobility in natural surroundings, hence their ability to work in dangerous environments such as mine fields [36]. Hexapods have good environmental adaptability and they can choose the best support point to fall when walking on the ground [19, 37]. In addition, Liu and Jing [19] emphasized that the bodies of hexapods are usually floated which enable them to avoid vibrations that may be caused by a terrain. Hexapods also consume low energy and move quite fast on uneven pavements [38]. Hexapod gaits can be classified into two. These include wave gait and tripod gait. In wave gait, pairs of legs move in a wavy form from the rear to the front while in tripod gait, three legs move at once while the other three legs provide a stable tripod for the robot. Hexapods also has two types of architecture [39]. These include the rectangular and hexagonal architectures. The rectangular shaped hexapod has six legs distributed symmetrically along two sides, each side having three legs while the hexagonal hexapod has legs distributed axi-symmetrically around the body, in a hexagonal or circular shape [39]. A typical example of a hexapod is RHex, which is as shown in Figure 5.

Fig 5: RHex [40]

3.1.6 Eight-Legged Robot or Hexapod

Octopods possess eight legs and they are therefore biologically inspired by spiders and other arachnids. They possess the greatest stability when compared with other legged robots. Figure 6 shows a typical example of an eight legged robot.

Fig. 6: Eight legged robot [41]

3.2 Locomotion in Wheeled Robots

Wheeled robots are robots that move on the ground with the aid of wheels. They are easy to control and direct when compared with legged robots. They consume less energy. Hence, they are suitable for applications with relatively low mechanical complexity and energy consumption [42]. Wheeled robots are faster than legged robots. They also provide a stable base on which a robot can maneuver [22]. Consequently, most mobile robots are designed with wheels. Nonetheless, wheeled robots are difficult to maneuver on rough terrains such as rocky or hilly terrains. Therefore, they are simply adequate for even terrains such as glass walls, concrete or brick wall and steal walls [11].Wheels can be classified as simple or standard wheels, castor wheels and multi directional wheels . A robot with a simple wheel has two degrees of freedom, castor wheels have rotation around its axis while multi directional wheels or omni wheels have three degrees of freedom that are achieved with the help of rollers mounted on the outer periphery of the wheels. The structure of wheeled robots can be classified according to the number of wheels they have. These include single wheel robot, two wheels robot, three wheels robot, and four wheels robot.

3.2.1 Single Wheeled Robot

A single wheeled robot has one wheel as it name implies. Single wheeled robots are usually unstable because they have just one point of contact with the ground [42]. Consequently, they are rarely used in practice. A typical example of a single wheel robot is a unicycle as shown in Figure7.

Fig.7: A single wheeled robot: murata girl [43]

3.2.2 Two Wheeled Robot

Two wheeled robots have two wheels which they use for locomotion. The basic challenge of two wheeled robot is that they find it difficult to maintain balance. There are two different positions for the wheels in a two- wheeled robot. In the first instance, the wheels can be parallel to each other. This type of two-wheeled robot is called a di-cycle. Alternatively, one wheel can be in front of the other. This type of two-wheeled robot is called a bicycle. The disadvantage of this type of robot is that it cannot maintain its balance when the robot stands still.

3.2.3 Three Wheeled Robot

Three wheeled robots are robots that possess three wheels for locomotion. Hence, they have three points of contact with the ground. Subsequently, a robot with three wheels is statically stable. A typical example of a three wheeled robot is the tricycle robot. A tricycle robot is usually designed with a front steering wheel and two rear wheels which are attached to a common axle driven by a single motor with two degrees of freedom either in a forward or reverse manner. This type of robot have a limited radius of curvature, hence they do not have the ability to turn 90^{o}. There are two types of the tricycle drive. These include the powered steered wheel and the unpowered steered wheel. In the powered steered wheel, the steering wheel is powered while the steering wheel is not powered for the unpowered steered wheel.

3.2.4 Four Wheeled Robot

Four wheeled robots are robots that move with the aid of four wheels. These types of robots are the most balanced types of robots because they hardly lose stability while moving. They can be controlled by using car like steering method. This method allows the robot to move in a car-like manner.

3.3 Locomotion in Tracked Robots

A tracked robot also referred to as a tractor crawler is a robot that runs on continuous tracks or threads rather than on wheels. They are best suited in rough and uneven terrains. Tracks have greater traction and greater area of ground contact; hence their ability to cross over large obstacles. Tracked robots adopt the skid steer drive for locomotion. The skid steer is a simple drive system that requires a large amount of power to turn and it is well known for slippage. They usually possess two tracks which are driven by two motors. One of the disadvantages of the tracked robot is that they require larger area to turn because their entire body is against the ground. A typical example of a tracked robot is the Nanokhod, a miniaturized track enabled robot which is as shown in Figure 8.

Fig.8: Nanokhod dual-track system [44]

3.4 Locomotion in Crawling Robots

Crawling animals are the models for crawling robots. Robots that exhibit this characteristic are usually referred to as soft robots because they are worm-like in nature. There are different types of crawling methods exhibited by robots that use crawling for locomotion. These methods include two-anchor crawling, peristalsis crawling and serpentine crawling. In two-anchor crawling, the robot moves by elongating and shortening at different degrees of friction [45, 46]. These types of robots are inspired by the movements of caterpillars. Robots also lengthen and shorten during peristalsis crawling. However, friction is not required during peristalsis crawling [46]. Robots that move by peristalsis crawling are biologically inspired by earth worms. Robots that move by serpentine crawling are biologically inspired by snakes. Locomotion in serpentine crawling are usually achieved using two approaches; these include the use of an active two-wheeled non-holonomic mobile robot whose body joint actuation provides the steering capability [47]. The second approach involves the conversion of the body joint actuation into a net forward locomotion that employs a frictional anisotropy utilizing either passive wheels or skates with the ground [48]. Figure 9 shows an articulated cord mechanism serpentine robot. The basic advantage of crawling robot is that most of their bodies are in contact with the ground and they can travel through narrow spaces which is difficult for both legged and wheeled robot [49]. They also possess the ability to climb through obstacles and steps whose heights matches their own. They are typically employed in pipeline/tunnel inspection and maintenance [50]. One of the disadvantages of the crawling robot is the difficulty of traversing rough terrains. They are also slow and complex to drive when compared to wheeled robots [49].

Fig 9: Articulated Cord Mechanism Serpentine Robot [51]

3.5 Locomotion in Flying Robots

Flying robots are biologically inspired by animals that employ wings for locomotion such as birds and flying insects. They use wings in two different flying gaits. These include gliding or fixed wing flight and flapping. In fixed wing flight, the wing of the robot does not provide the thrust; rather the wing has a relative velocity, v, in relation to the air. This generates two orthogonal forces based on the shape of the wing. These forces include the lift force and the drag force. The lift force elevates the robot from the ground, while the drag force resists the forward movement of the robot [46]. In flapping wing flight, the movement of the wings provides the drag and lift forces. A typical example of a flying robot that flaps its wing is the Robofly, a laser powered robot developed at the University of Washington. Robofly is envisioned to detect gas leaks in walls or pipe-filled chemical plants as well as perform crop surveys for farmers [52]. Figure 10 shows the picture of Robofly.

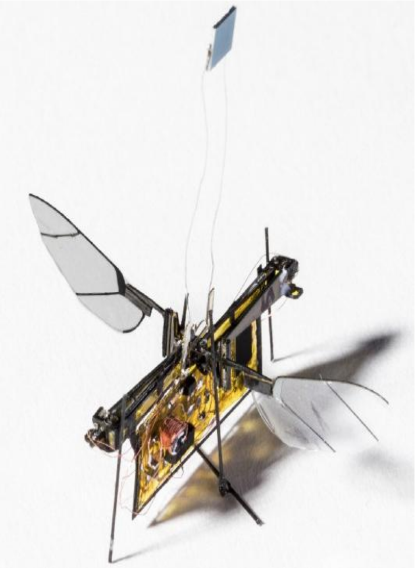

Fig. 10: Robofly [52]

3.6 Locomotion in Hybrid Robots

Hybrid robots are robots that consist of a combination of two or more mobility concepts such as wheel-leg, track-wheel, and leg-wheel-track. Wheeled-legged robots are robots that exhibit the advantages of both legged and wheeled robots. For instance, they possess great speed and they are energy efficient like wheeled robots; and they also possess the ability to move on rough or uneven terrains like the legged robots. In an ideal situation, a wheeled-legged robot moves on its wheels to make it move faster. However, it switches to its legs when it encounters a rough or an uneven terrain. A good example of a wheeled-legged is the All-Terrain Hex-legged Extra-Terrestrial Explorer (ATHLETE) and Boston dynamics Handle. ATHLETE is as shown in Figure 10. Another typical example of a hybrid robot is Snake Robo, a robot that slither like a snake and walk like a robot with two legs.

Fig. 10: ATHLETE [53]

4. ADHESIVE MECHANISM IN CLWAR

It is important to note at this point that in addition to locomotion mechanisms, a CLWAR must be able to attach itself to diverse surfaces reliably. Adhesive mechanisms in CLWAR include the use of suction force adhesion, magnetic adhesion, thrust force, grippers and bio-inspired adhesion.

4.1 Suction Force

The suction force adhesion is the most widely used adhesion mechanism in CLWAR. This technique usually involves the use of two or more vacuum cups on each feet of the robot. This is to prevent the loss of pressure which could be caused by surface curvature or irregularities [54]. The advantage of this technique is that the vacuum cups are light and easy to control which allows the CLWAR to climb over surfaces that are made of different types of materials [1]. The suction force adhesion technique is however characterized by some drawbacks. First, the suction force adhesion mechanism consumes a lot of time because it takes a lot of time to develop the vacuum cup. This delay according to Silva and Machado [1] may reduce the speed at which the robot moves. Second, the robot can fall if there is any gap in its seal [1, 55]. A typical example of a robot that employs this mechanism is the RAMR1.

4.2 Magnetic Force

This technique involves the use of electromagnets, permanent magnets or magnetic wheels to adhere to surfaces. Hence, it is suitable only in environments that have ferromagnetic surfaces. This technique is fast, reliable and does not need energy for the adhesion process [11]. However, they are not energy efficient.

4.3 Rope/Rail Gripping

This technique involves the use of a rope ascender attached to the upper section of a specialized equipment that is installed on a wall to support a navigating robot platform [5]. This technique is usually adopted for cleaning a façade window [56]. The advantage of this technique is that it ensures the safety of the robot since it is secured to a high platform through a rope. A typical example of this type of robot is sloth; this is as shown in Figure 11.

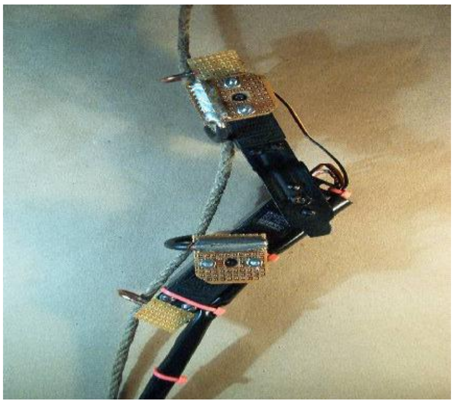

Fig. 11: Sloth, a rope climbing robot [57]

4.4 Bio-Inspired Technology

This technique mimics the characteristics of climbing animals that navigate over vertical wall surfaces. Such animals include insects, beetles, skinks, anoles, frogs and geckos. Hence, bio-inspired adhesive technology has been classified into gecko inspired synthetic dry adhesives, micro-structured polymer feet and microspines [55]. Dry adhesives are usually caused by van der Waals forces, hence CLWAR that utilize this mechanism can move on almost any surface [55]. The van der Waals forces can be quantitatively characterized by equation (4).

$$F = \frac{A_H}{12\pi D^3} \qquad (4)$$

Where F is the force of interaction, A_H is the Hamaker constant and D is the distance the two surfaces.

According to Silva et al. [55], dry adhesives are more robust than the suction adhesion mechanism. In addition, energy is not required to maintain attachment after it has been initiated [56]. In addition, gecko-inspired synthetic dry adhesives are fast and reliable in climbing at any orientation and any surface. However, their self-cleaning capability is not mature, which makes them prone to dusts. They are also very expensive [12]. A typical example of a robot that use the gecko inspired synthetic dry adhesive is the stickybot, a mechanical lizard like robot shown in Figure 12.

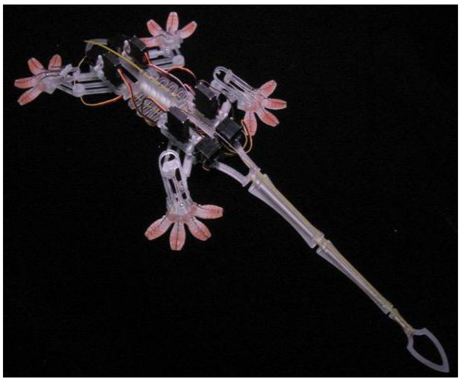

Fig 12: Stickybot [58]

Microspines are biologically inspired by insects and spiders. They employ arrays of miniature spines which do not infiltrate surfaces. This mechanism enables the robots to move on hard vertical surfaces such as concrete, brick, stucco and masonry [59]. They are quiet during locomotion; they consume less energy and are adaptable to dusty, moist and porous surfaces [12]. The disadvantage of this type of adhesive mechanism is that it prevents the CLWAR from climbing on smooth surfaces. They also find it hard to overcome large obstacles, and are subjected to plastic deformation and wear [12].

4.5 Grippers

Robots that deploy grippers for adhesion use gripping systems attached to the extreme end of their limbs for attaching to surfaces [60]. They are suitable for flat walls and ceilings. The major challenge of grippers is that they find it difficult to move on irregular environments and rough surfaces such as poles, pipes, bridges, beams and columns, wire meshes, natural environments and man-made structures [12]. Example of this kind of robot is the ROMA 1 robot.

4.6 Thrust Force

This adhesive mechanism is basically used in submerged applications such as chemical storage tanks submerged in water. Robots with this type of adhesive mechanism easily cope with obstacles. An example of a robot employing this type of adhesive mechanism is the RobTank climbing robot [1].

4.7 Electroadhension

Electroadhesion is defined by Yehya et al. [61] as an electrically controllable adhesion technology. The principle field of electroadhesion is the electrostatic field. This field produces an attractive force which is lower than that of the magnetic force [61]. CLWAR employing this technique are simple, light, fast and they also consume low energy [62].

4.8 Hot Melt

Hot melt adhesive are also known as hot glue. They consist of polymers. Hence, CLWAR using this mechanism for adhesion have strong adaptability to solid surfaces and unstructured terrains [12]. Their drawbacks include slow speed and large energy consumption. They also leave traces behind them during locomotion [63].

5. APPLICATIONS AND CHALLENGES OF CLWAR

CLWARs have been applied in diverse fields. The applications of CLWAR in diverse fields are summarized in Table 1. Table 2 also presents the challenges of CLWAR by locomotion while Table 3 is a summary of the problems confronting CLWAR by adhesive mechanism.

Table 1. Applications of CLWAR

Application area	Example of robot, function and Author	Locomotion/ adhesive mechanism of robot
Maritime Industry	Rest 1 Climbing Robot: used for butt-welding of ship hull skin [64]	six reptile-type legs / electromagnets
Consolidation and monitoring of geological tasks	Roboclimber: It is used for ensuring the precise monitoring of geological tasks [65]	quadruped/ rope gripping
Surveillance	Zafar and Hussain [66] climbing robot: It is used for rescue operations, military operations and scientific researches	wheels/ rope gripping
Sanitation	Filius and Cleanbot II: They are used for cleaning tall walls [67], [68]	wheels and track-wheel mechanism/ Rope gripping and suction pads
Welding	Welding robot: for welding diverse parts together [11]	legged/ electromagnets
space exploration	Lemur IIb: used for climbing steep terrain during space exploration [69]	quadruped/ gripper
in-service inspection of the floor and walls of oil, petroleum and chemical storage tanks	RobTank: Used for the inspection of the floor and walls of oil, petroleum and chemical storage tanks [70]	wheels/ thrust force
urban reconnaissance	RAMR1: for eliciting information about a hostile situation within a building [71]	biped / suction cup
mine exploration	Autonomous Legged Underwater Vehicle (ALUV): mining and hunting in surf zones, locating mines and obstacles[72]	hexapod/ biologically inspired
repair of energy transmission lines	pole climbing robot: resolving issues relating to power transmission lines [73]	wheels/ grippers
Painting	wall painting robot: responsible for painting the walls of flat buildings [74]	robotic arms/ vacuum cups
Detection of surface cracks in walls	Hex-piderix: detects the surface cracks in walls and roofs of buildings [75]	hexapod/suction cup

Table2. Challenges of CLWAR

Principles of Locomotion	Challenges	Adhesion Mechanism	Challenges
Legs	Slow, heavy, complex control system.	Suction Force	Requires a lot of time to develop the vacuum cup. Robot may move at a slow speed
Wheels	can cause damage on the ground, difficulty in maneuvering rough terrains	Magnetic Force	work only in places with ferromagnetic surfaces
Tracks	require a large amount of power to turn	Rope Gripping	More energy might be needed to climb the rope
Crawling	Slow, difficulty in maneuvering rough terrains	Hot melt	slow and consume large amount of energy
Wings	Expensive to build	Bio-inspired	prone to dusts and also very expensive to develop
Hybrid	complex and have heavier structures	Thrust Force	Robots may find it difficult to locate their paths in complex environments

6. A FRAMEWORK FOR THE EFFECTIVE DESIGN OF A CLWAR

In spite of the numerous benefits of CLWAR in diverse applications, their performances are still unsatisfactory. This is chiefly because the problem of locomotion and adhesion still exists in CLWARs. Based on these challenges, this study proposed a framework as shown in Figure 13 that can be considered during the design of a CLWAR.

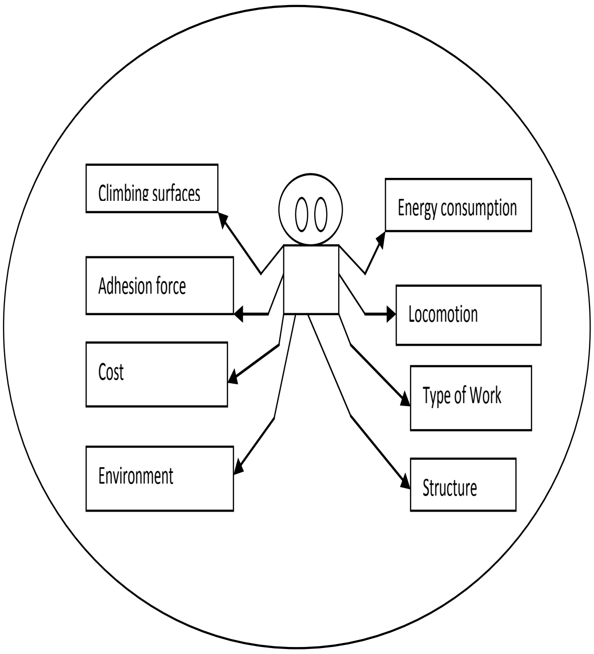

Fig. 13: A Framework for the effective design of a CLWAR

The framework suggests that climbing surfaces, adhesion force, cost, and the type of environment that the robot will work in are necessary for the design of a CLWAR. The framework also recommends that the amount of energy consumed, the locomotion principles, the type of work that the robot will perform as well as the structure of the robot is important for the effective design of a CLWAR.

6.1 Climbing Surfaces

A CLWAR should be designed to be adaptable to different surfaces made up of diverse materials such as walls, floors, glasses and ceilings.

6.2 Adhesion Force

A CLWAR must be designed to have a high adhesion force. This will enable the robot to have strong adaptability to any solid surfaces and unstructured terrains. It will ensure the safety of the robot by preventing it from falling.

6.3 Amount of Energy Consumed

A CLWAR should consume less energy while moving and attaching to surfaces.

6.4 Environment

One of the major goals of a CLWAR is to work in environments that are hazardous and very difficult to access by human beings. Hence, a CLWAR should be designed to adapt to both structured and unstructured environments as well as even and uneven terrains.

6.5 Cost

The design of a CLWAR must be cost effective. A CLWAR must not be too expensive to build.

6.6 Locomotion

A CLWAR must have a good locomotion mechanism. It must be able to walk as well as climb diverse surfaces reliably at any direction. A CLWAR should also be designed to be fast in locomotion as well as easy to control.

6.7 Type of Work

The task that a CLWAR would perform should be considered during its design. This will inform the type of locomotion mechanism that will be used. For instance, it will be difficult to use a biped robot for painting a high rise building.

6.8 Structure

A CLWAR should not be designed to be complex in nature. It should be simple and light in weight. This will ensure the stability of the robot.

7. CONCLUSION

This study examines climbing and walking robots paradigms. This is because they are very useful in activities that are too dangerous for human beings to perform. Locomotion and adhesion principles of CLWAR were extensively reviewed. The study revealed that there are different locomotion mechanisms for CLWAR. These include legs, wheels, tracks, wings or a combination of two or more of the locomotion concepts. With regards to adhesion principles, suction force, magnetic force, ropes, grippers and van der Waals forces can be applied. Furthermore, the study appraises the applications and challenges of CLWAR. The study showed that CLWAR can be applied in diverse areas such as maritime industry, sanitation purposes, painting, surveillance and the repair of transmission lines. However, the use of CLWAR is inadequate because their performances are usually unsatisfactory because they still have issues with their locomotion and adhesion techniques. Consequently, this study recommends that a CLWAR must have a good locomotion mechanism that will enable it to walk and climb diverse surfaces reliably at any orientation. The study also recommends that the adhesion force of a CLWAR must be high so as to prevent it from falling during climbing or walking. Other factors recommended by the study during the design of a CLWAR include the type of tasks to be performed, the working environment, the structure of the CLWAR, the climbing surfaces and the amount of energy consumed.

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